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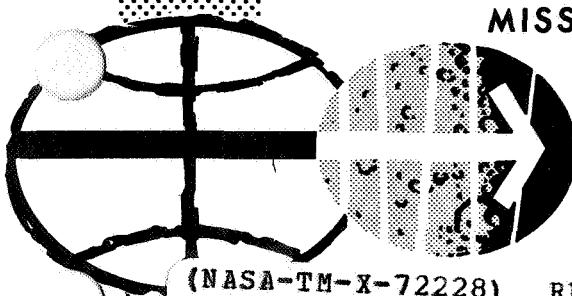
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REVISION I  
TO THE APOLLO MISSION G  
SPACECRAFT REFERENCE TRAJECTORY  
VOLUME I  
REFERENCE MISSION PROFILE  
(LAUNCHED AUGUST 14, 1969)

Lunar Mission Analysis Branch, Landing Analysis Branch,  
and Orbital Mission Analysis Branch

MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER  
HOUSTON, TEXAS



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PROJECT APOLLO

REVISION 1 TO THE APOLLO MISSION G SPACECRAFT  
REFERENCE TRAJECTORY  
VOLUME I - REFERENCE MISSION PROFILE  
(LAUNCHED AUGUST 14, 1969)

By Lunar Mission Analysis Branch, Landing Analysis Branch,  
and Orbital Mission Analysis Branch

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February 7, 1969

MISSION PLANNING AND ANALYSIS DIVISION  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
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REVISION 1 TO THE APOLLO MISSION G SPACECRAFT

REFERENCE TRAJECTORY

VOLUME I - REFERENCE MISSION PROFILE

(LAUNCHED AUGUST 14, 1969)

Lunar Mission Analysis Branch, Landing Analysis Branch,  
and Orbital Mission Analysis Branch

1.0 SUMMARY AND INTRODUCTION

Only mission phases which have been changed since the publication of the Apollo Mission G spacecraft reference trajectory are included in this revision. These phases are LOI, LM descent and ascent, LM/CSM rendezvous, TEI, and reentry. This volume and Volume II (ref. 1) revise reference 2, the mission profile, and reference 3, the trajectory parameters for the profile, respectively. The launch date for the profile is August 14, 1969; the launch azimuth is 72°; and the translunar injection occurs during the second orbit over the Atlantic. The lunar landing site is II-P-2, located at a selenographic longitude of 34° E and a selenographic latitude of 2.75° N.

LOI-1, LOI-2, and CSM plane-change maneuvers show corrected external ΔV components. The coordinate system was updated to be compatible with the CMC.

The revisions to the LM descent and ascent phase are as follows:

1. The DPS thrust and specific impulse profiles were updated (ref. 4).
2. The ΔV imparted by the CSM during the LM/CSM separation maneuver prior to DOI was increased from 0.5 fps to 2.5 fps (TCR G-4).
3. The guidance targets in onboard programs P63 and P64 were changed in an effort to reduce thrust and pitch sensitivity to terrain features during powered descent (TCR G-2). The new targeting for the descent was taken from reference 5. Note, however, that the simulated ignition logic used does not reflect the latest onboard logic described in reference 6. This simulation will be updated for the next revision of this document.

4. The lunar surface stay time was reduced from about 26 hours to about 22 hours (TCR G-3).

5. The LM to CSM phase angle at LM insertion was increased from  $16.22^\circ$  to  $20.85^\circ$  to accommodate improved rendezvous techniques (TCR G-1).

The rendezvous profile presented in section 4.4 reflects the following changes (TCR C-1). It does not reflect TCR G-7, which was approved after the profile in section 4.4 was generated. The appendix presents a profile reflecting TCR G-7 (i.e., a 4- by 45-n. mi. altitude insertion orbit, a positive radial rate at insertion, and slight modifications to the time interval between maneuvers).

1. Platform (fine) alignments are scheduled for both the LM and CSM between LM insertion and CSI.

2. A plane-change capability is scheduled within the CSI-to-CDH phase to eliminate insertion out-of-plane dispersions.

3. The logic option which makes the  $\Delta t$  between CSI and CDH essentially constant, regardless of dispersions, is incorporated.

4. TPI is at the midpoint of darkness about 147 minutes after insertion.

5. The total  $\Delta t$  from insertion to completion of terminal braking is about 3 hours 15 minutes.

6. The approximate  $\Delta t$ 's between maneuvers are insertion to CSI, 55 minutes; CSI to CDH, 58 minutes (PC occurs 29 minutes prior to CDH); CDH to TPI, 34 minutes; and TPI to end of braking, 48 minutes ( $130^\circ$  of CSM travel).

7. All in-orbit rendezvous maneuvers are RCS Z-axis burns.

TEI and the reentry profile reflect new entry targeting and a shorter reentry range (TCR G-6).

The following are the revisions to the reentry phase (TCR G-6):

1. The nominal reentry target range has been changed from 2000-n. mi. down-range to 1350-n. mi. down range in order to make the primary reentry mode compatible with the backup mode.

2. Logic was added to the guidance program to prevent roll reversals at drag levels greater than  $140 \text{ ft/sec}^2$ . The previous logic allowed this kind of reversal, which could cause considerable miss distance.

3. The reentry flight-path angle has changed from  $-6.40^\circ$  to  $-6.48^\circ$  as a result of a slight shift in the steep target line. Thus, the initial maximum load factor increased to a value greater than that previously published.

4. The EMS scroll pattern has been finalized and this document reflects the finished version.

## 2.0 ABBREVIATIONS

|                 |  |
|-----------------|--|
| AOFG            | acceleration target for the LM descent guidance frame <sup>a</sup> braking phase   |
| AIFG            | acceleration target for the LM descent guidance approach phase   |
| APS             | ascent propulsion system   |
| c.g.            | center of gravity  |
| CM              | command module   |
| CSM             | command and service modules  |
| DOI             | descent orbit insertion  |
| DPS             | descent propulsion system  |
| DSKY            | display keyboard   |
| EI              | entry interface  |
| EMS             | entry monitoring system  |
| GCS             | guidance coordinate system   |
| JOFG(3)         | Z component at the jerk target for the LM descent guidance braking phase   |
| JIFG(3)         | Z component at the jerk target for the LM descent guidance approach phase  |
| $K_x, K_y, K_v$ | coefficients used to scale correction terms due to deviations in spacecraft altitude, landing site out-of-plane distance, and speed, respectively, in the computation of braking phase initiation time |

---

<sup>a</sup>The guidance frame is defined as follows: The origin is at the current landing site, the X-axis is along the landing site radius, the Z-axis is in the trajectory plane at the phase terminus in the direction of motion, and the Y-axis completes the right-handed system.

|                         |  |
|-------------------------|--|
| LM                      | lunar module   |
| LOI                     | lunar orbit insertion  |
| PC                      | plane change   |
| PDI                     | powered descent initiation   |
| PGNCS                   | primary guidance, navigation, and control subsystem  |
| REFSMMAT's <sup>a</sup> | <p>Transformation matrix from an Earth-centered inertial Cartesian coordinate system to an IMU coordinate system, where the IMU is aligned as follows:</p> <p>Launch pad: X-axis along launch azimuth at pad; Z-axis down local vertical (along negative radius vector); and Y-axis completes right handed system.</p> <p>LM descent (through lunar stay): X-axis along local vertical of landing site at time of touchdown; Z-axis in the CSM orbit plane in direction of flight perpendicular to X; and Y-axis along negative angular momentum vector.</p> <p>LM ascent (lift-off through TEI): X-axis along local vertical of landing site at time of lift-off; Z-axis is in CSM orbit plane in direction of flight perpendicular to X; and Y-axis is along negative angular momentum vector.</p> <p>Entry: X-axis is in local horizontal plane in direction of flight at entry interface (400 000 ft); Z-axis is down along negative radius vector at entry interface; and Y-axis is along negative angular momentum vector.</p> |
| ROFG                    | position target for the LM powered descent guidance braking phase  |

---

<sup>a</sup>Only the REFSMMAT's and applicable maneuvers documented in this revised reference trajectory are shown.

|          |  |
|----------|--|
| R1FG     | position target for the LM powered descent guidance approach phase   |
| R1GXG    | desired component of the spacecraft position in the X-direction of the GCS at braking phase initiation             |
| R1GZG    | desired component of the spacecraft position in the Z-direction of the GCS at braking phase initiation             |
| TCR      | trajectory change request  |
| TENDBRAK | limiting value of TGO which terminates the braking phase   |
| TENDAPPR | limiting value of TGO which terminates the approach phase  |
| TGO      | time to go   |
| VOFG     | velocity target for the LM powered descent guidance braking phase  |
| V1FG     | velocity target for the LM powered descent guidance approach phase   |
| V1GG     | desired magnitude of spacecraft velocity vector with respect to the lunar landing site at braking phase initiation |

## 3.0 INPUT DATA

The following input was used to compute revision 1 to the Mission G reference trajectory:

|   |                      |
|---|----------------------|
| Lunar landing sites . . . . .                               | reference 2          |
| Spacecraft weights . . . . .                                | table I              |
| SM and LM engine performance<br>data . . . . .              | table II             |
| CM RCS engine performance data . . . . .                    | reference 7          |
| LM braking gates . . . . .                                  | table III            |
| CM mass properties for entry . . . . .                      | table IV             |
| Conditions at entry interface<br>and target point . . . . . | table V              |
| Aerodynamic coefficients . . . . .                          | table VI             |
| Parachute aerodynamics . . . . .                            | reference 7          |
| Aerodynamic heating data . . . . .                          | references 8 and 9   |
| Reentry digital auto pilot . . . . .                        | references 10 and 11 |
| Atmospheric model . . . . .                                 | reference 12         |
| MSFN station locations . . . . .                            | reference 13         |

## 4.0 PROFILE DESCRIPTION OF THE REVISED PORTIONS OF MISSION G

### 4.1 LM Undocking to PDI

During the tenth orbit after the circularization maneuver, the LM and CSM undock in preparation for lunar landing. The CSM is undocked (0.5-fps  $\Delta V$ ) from the LM approximately 2.5 hours (1.25 revolutions) prior to landing, and is allowed to reach a separation distance of 40 ft. Stationkeeping is initiated at this point, and the LM is rotated about its longitudinal axis so the CM pilot can observe the landing gear. Twenty-five minutes after undocking (1 revolution prior to PDI) the CSM performs a 2.5-fps (increased from 0.5 fps) separation maneuver directed radially downward toward the moon's center. This maneuver provides a LM/CSM separation distance at DOI of 2.9 n. mi. The DOI occurs 0.5 revolutions after separation and places the LM in a 60-n. mi. altitude by 50 000-ft altitude orbit with the pericynthion located to the east of the landing site longitude by a central angle of approximately  $15^\circ$ . PDI occurs at pericynthion of the descent orbit. Figure 1 shows the trajectory parameters from LM separation through DOI to touchdown. Included are time histories of LM altitude and LM-to-CSM relative parameters, as well as relative motion plots. The following table shows the events from undocking through the post-DOI coast period.

| Event                | Time,<br>hr:min | Duration,<br>min:sec | Propulsion<br>system | $\Delta V$ ,<br>fps | Propellant,<br>lb |
|----------------------|-----------------|----------------------|----------------------|---------------------|-------------------|
| Undocking            | 96:49           | --                   | --                   | 0.5                 | --                |
| Nulling              | 96:50           | 0:03                 | SM RCS               | 0.5                 | 2                 |
| CSM/LM<br>separation | 97:13           | 0:07                 | SM RCS               | 2.5                 | 10                |
| LM ullage            | 98:12           | 0:07.5               | LM RCS               | 1.4                 | 6                 |
| DOI                  | 98:12           | 0:27.5               | LM DPS               | 70.2                | 238               |
| Coast                | 98:12           | 56:48                | --                   | --                  | --                |

The target load for the DOI maneuver is given in table VII(a).

#### 4.2 Powered Descent

The powered descent maneuver is initiated at pericynthion of the descent transfer orbit. The powered descent consists of three main phases: braking, approach, and landing. The braking phase is designed for efficient reduction of the orbital velocity. The final approach phase is designed to provide pilot visual (out-the-window) monitoring of the approach to the surface. The landing phase is also designed to provide visual assessment of the landing site and to provide compatibility for pilot takeover from the automatic control. Figure 2 describes trajectory parameters for the entire powered descent. Figure 3 describes the trajectory parameters in more detail for the approach and landing phases. Included in figures 2 and 3 are time histories of LM altitude, velocity, flight-path angle, descent rate, horizontal velocity, surface range, LDP angle, thrust angle, thrust magnitude, and LM-CSM relative parameters as well as an altitude range profile and an altitude - altitude-rate profile. These trajectory parameters were generated on the assumption that perfect landing radar updating and a smooth terrain existed. The effects of local terrain variations and radar updating are shown in reference 14.

A one-phase guidance concept has replaced the two-phase guidance scheme used to target the powered descent. Previously the guidance had to satisfy a set of high-gate conditions and a set of low-gate conditions. The one-phase guidance must satisfy only a set of low-gate conditions. This new guidance scheme reduces the sensitivity of thrust and pitch attitude to terrain features during powered descent. The powered descent maneuver (LM DPS) is described below:

|                              |        |
|------------------------------|--------|
| Duration, min:sec . . . . .  | 11:18  |
| DPS propellant, lb . . . . . | 16 120 |
| $\Delta V$ , fps . . . . .   | 6 562  |

The mission shadow time for LM descent (from undocking to touchdown) is given below:

| Lighting       | Enter,<br>hr:min:sec | Exit,<br>hr:min:sec |
|----------------|----------------------|---------------------|
| Sunlight       | (a)                  | 97:27:16.9          |
| Lunar penumbra | 97:27:16.9           | 97:27:27.9          |
| Lunar umbra    | 97:27:27.9           | 98:13:26.5          |
| Lunar penumbra | 98:13:26.5           | 98:13:37.7          |
| Sunlight       | 98:13:37.7           | (b)                 |

<sup>a</sup>Undocking occurs in sunlight.

<sup>b</sup>Landing site in sunlight

The target load for LM descent is given in table VII(b). The MSFN timeline for LM descent is given in table VIII.

**4.2.1 Braking phase.**- The ullage and DPS engine gimbal trim periods are performed at the constant inertial attitude required by PGNCS guidance at DPS ignition. The braking phase utilizes quadratic acceleration guidance equations. The spacecraft is initially in a windows-down attitude until approximately 35 000 ft. Then the spacecraft is rotated about the vehicle X-axis to a windows-up attitude so the landing radar can be used beginning at 30 000 ft. The phase is characterized by the following:

Initiation time, hr:min:sec g.e.t. . . . . 99:09:20.2

Braking sequence:

|  |      |
|--|------|
| Ullage using two RCS +X translation<br>thrusters, sec . . . . .        | 7.5  |
| DPS minimum thrust (engine trim period),<br>sec . . . . .              | 26   |
| DPS-FTP (92.5 percent rated thrust),<br>min:sec . . . . .              | 6:18 |
| Throttle recovery (near 57 percent rated<br>thrust), min:sec . . . . . | 1:32 |

Termination:

|                                    |        |
|------------------------------------|--------|
| Altitude, ft . . . . .             | 7 262  |
| Range, ft . . . . .                | 30 546 |
| Horizontal velocity, fps . . . . . | 516    |
| Altitude rate, fps . . . . .       | -87.7  |
| Time-to-go, sec . . . . .          | 159    |
| Total duration, min:sec . . . . .  | 8:24   |
| Total DPS propellant, lb . . . . . | 13 957 |
| Total ΔV, fps . . . . .            | 5 397  |

**4.2.2 Approach phase.**- The approach phase is targeted to conditions for vertical descent (77-ft altitude and 3.1-fps descent rate). The look angle to the landing site is greater than 7° above the lower window edge for the entire phase ( $2^m 34^s$ ) and greater than 10° for the last 1 minute 28 seconds. The thrust level varies between 4344 and 3500 lb.

4.2.3 Landing phase.- The landing phase begins at a point designated as low gate where the crew can take over manual control (approximately 500-ft altitude). However, the trajectory described herein is based on automatic guidance control. This phase uses the same guidance and targets as the approach phase until the beginning of vertical descent (except for the last 10 seconds during which linear acceleration guidance is used). The look angle to the landing site is greater than 10° above the lower window edge for the first 24 seconds of the landing phase. The vertical descent portion of the landing phase starts at an altitude of 77 ft and is terminated at touchdown on the lunar surface. The guidance is a rate of descent command mode. Nominally, a 3-fps rate of descent is used throughout the vertical descent. The landing phase is described below:

|   |          |
|---|----------|
| Phase duration, min:sec . . . . .                           | 1:04     |
| Low gate to beginning of vertical<br>descent, sec . . . . . | 44       |
| Vertical descent, sec . . . . .                             | 20       |
| Lunar touchdown, hr:min:sec,<br>g.e.t. . . . .              | 99:20:38 |
| Sun elevation angle at landing,<br>deg . . . . .            | 7.4      |
| Lunar landing site location:                                |          |
| Latitude, deg N . . . . .                                   | 2.75     |
| Longitude, deg E . . . . .                                  | 34.0     |
| Lunar stay time, hr:min:sec . . . . .                       | 21:40:07 |

#### 4.3 CSM Plane Chang

At approximately 41<sup>h</sup>56<sup>m</sup> after LOI, the CSM performs a plane change to place the LM in the CSM orbit plane at the time of LM lift-off.

|  |               |
|--|---------------|
| Burn initiation, hr:min:sec,<br>g.e.t. . . . . | 118:29:14.484 |
| Duration, sec . . . . .                        | 8.40          |
| Plane change, deg . . . . .                    | 1.61          |

|  |        |
|--|--------|
| $\Delta V$ , fps . . . . . . . . . . . | 150.00 |
|--|--------|

|                                      |     |
|--------------------------------------|-----|
| SPS propellant, lb . . . . . . . . . | 535 |
|--------------------------------------|-----|

The maneuver is performed approximately 1.25 revolutions prior to LM lift-off to provide one complete front-side pass for tracking prior to LM ascent.

#### 4.4 LM Ascent and Rendezvous

The rendezvous profile presented below reflects TCR C-1. It does not reflect TCR G-7, which was approved after the profile below was generated. The appendix presents a profile reflecting TCR G-7 (i.e., a 4- by 45-n. mi. altitude insertion orbit, a positive radial rate at insertion, and slight modification to the time interval between maneuvers).

4.4.1 Main ascent.- The LM ascent begins after a lunar stay time of approximately 22 hours (reduced from 26 hours). The vertical rise is maintained until a radial rate greater than 50 fps is achieved. Yaw steering is used during ascent, if required, to maneuver the LM into an orbit coplanar with the CSM orbit ( $< 0.5^\circ$ ). The target load for ascent is given in table VII(c). Figure 4 shows trajectory parameters from lunar lift-off to orbit insertion. Included are time histories of LM altitude, LM-CSM relative parameters, LM S-band antennae angles, LM rendezvous radar angles, a range - range-rate profile, and a relative motion plot. Main ascent is characterized by the following:

|  |               |
|--|---------------|
| LM ascent initiation, hr:min:sec, g.e.t. . . . . | 121:00:44.795 |
|--|---------------|

|  |    |
|--|----|
| Vertical rise, sec . . . . . . . . . . . | 10 |
|--|----|

|  |  |
|--|--|
| LM insertion orbit (relative to mean<br>lunar radius): |  |
|--|--|

|   |        |
|---|--------|
| Pericynthion altitude, ft . . . . . . . . . | 55 152 |
|---|--------|

|  |         |
|--|---------|
| Apocynthion altitude, ft . . . . . . . . . | 177 747 |
|--|---------|

|  |  |
|--|--|
| LM insertion orbit (relative to landing<br>site radius): |  |
|--|--|

|   |        |
|---|--------|
| Pericynthion altitude, ft . . . . . . . . . | 60 123 |
|---|--------|

|  |         |
|--|---------|
| Apocynthion altitude, ft . . . . . . . . . | 182 717 |
|--|---------|

|   |      |
|---|------|
| Ascent thrust duration, min:sec . . . . . . . | 6:53 |
|---|------|

|  |         |
|--|---------|
| CSM lead angle at burnout, deg . . . . . | 20.85   |
| APS propellant, lb . . . . .             | 4 929   |
| $\Delta V$ , fps . . . . .               | 6 011.5 |

4.4.2 Coelliptic sequence initiation maneuver.- At LM insertion into the standard 29.2- by 9.1-n. mi. altitude orbit, the CSM (central) lead angle is approximately  $21^\circ$ , and the relative range is approximately 355 n. mi. The nominal CSM orbit is about a 58-n. mi. altitude, circular one. Fifty-five minutes after insertion, just prior to LM apocynthion, the CSI maneuver is performed. This horizontal posigrade maneuver of approximately 49 fps requires about 44 seconds of RCS (+Z) thrusting. If an out-of-plane situation should exist (nominally, it would not) and be determined prior to CSI (by sextant tracking), an out-of-plane component designed to force a common node  $90^\circ$  later would be incorporated in the CSI maneuver. Then at this common node, a separate PC maneuver would be performed with the RCS Y-thrusters. The post-CSI LM orbit is roughly 44- by 29-n. mi. altitude. Table VII(d) gives the target load for CSI.

4.4.3 Constant  $\Delta H$  maneuver.- CDH is performed about 58 minutes after CSI or 29 minutes after PC. CDH is now designed to occur half the LM orbital period (essentially  $180^\circ$ ) after CSI, not at the resulting apocynthion following CSI as for the previous profiles. This near-horizontal, posigrade, coelliptic maneuver of approximately 22 fps involves a radial-up component of 5 fps. The RCS (+Z) burn duration is approximately 19 seconds. An out-of-plane component might also be incorporated in the CDH maneuver either if the plane change were not started until PC or if it were started at CSI and (due to dispersions) a common node had not resulted at PC. The procedure for each of the plane-change maneuvers is to null the out-of-plane velocity. If performed at a common node, such a maneuver makes the vehicles coplanar; if not performed at a common node, such a maneuver establishes a common node  $90^\circ$  later. Any out-of-plane situation resulting at insertion would therefore normally be eliminated either at PC or at CDH. The target load for CDH is given in table VII(e).

4.4.4 Terminal phase initiation.- After CDH the LM coasts in the coelliptic orbit (roughly 43-n. mi. altitude, circular) with a coelliptic  $\Delta h$  of approximately 15 n. mi. for about  $3\frac{1}{4}$  minutes to TPI, which is at the midpoint of darkness. The line-of-sight TPI maneuver of approximately 25 fps, and a 23-second RCS (+Z) burn is initiated when the LM-to-CSM elevation angle is  $26.6^\circ$ . TPI is targeted to establish an intercept of the vehicles after  $130^\circ$  of CSM travel. The target loads are given in table VII(f). The  $\Delta t$  between TPI and the theoretical intercept velocity match (TPF) is approximately 43 minutes. Terminal phase (nominally-zero) midcourse correction maneuvers are scheduled at 15 and 30 minutes after TPI, each targeted for the original TPI-targeted intercept.

**4.4.5 Terminal phase finalization.**- The  $\Delta V$  for the theoretical TPF is approximately 32 fps. It should be assumed, however, that as much as twice the theoretical TPF value is operationally required for the midcourse maneuvers and braking, including line-of-sight control during braking. The nominal braking gate maneuvers (table III) begin about 3 minutes prior to the theoretical TPF at a relative range of 1 n. mi., and braking is completed approximately 5 minutes after the theoretical TPF. In addition, the PGNCS external  $\Delta V$  targets and gimbal angles at maneuver initiation are presented for each of the rendezvous maneuvers in table IX.

Latitude versus longitude curves for the CSM and LM during the rendezvous phase are presented in figures 5(a) and 5(c), respectively. A time history of LM altitude from insertion through docking is presented in figure 5(b). Time histories of LM velocity and flight-path angles are presented in figures 5(d) and 5(e), respectively. Time histories of pertinent rendezvous parameters such as LM-CSM elevation angle, CSM-LM-sun angle, CSM-LM-earth angle, CSM phase angle, and LM-CSM range and range rate are presented in figures 5(f) through 5(k). Relative motion curves for the rendezvous sequence are shown in figures 5(l) and 5(m).

#### 4.5 Transearth Injection

Transearth injection is initiated  $14^{\text{h}}09^{\text{m}}$  after TPI; the total time in lunar orbit is  $61^{\text{h}}09^{\text{m}}$ . The TEI burn was designed for a 93-hour transearth flight time. It is characterized by the following:

|  |             |
|--|-------------|
| Initiation, hr:min:sec, g.e.t. . . . . | 137:43:30.2 |
|--|-------------|

|                            |       |
|----------------------------|-------|
| Latitude, deg S . . . . .  | 3.9   |
| Longitude, deg W . . . . . | 146.2 |

|                              |       |
|------------------------------|-------|
| Burn duration, sec . . . . . | 133.4 |
|------------------------------|-------|

|                                   |        |
|-----------------------------------|--------|
| SPS propellant used, lb . . . . . | 8480.4 |
|-----------------------------------|--------|

|                             |     |
|-----------------------------|-----|
| Plane change, deg . . . . . | 0.9 |
|-----------------------------|-----|

##### Burnout:

|                                  |       |
|----------------------------------|-------|
| Flight-path angle, deg . . . . . | 3.0   |
| Altitude, n. mi. . . . .         | 60.8  |
| Latitude, deg S . . . . .        | 2.8   |
| Longitude, deg W . . . . .       | 154.6 |

|                            |        |
|----------------------------|--------|
| $\Delta V$ , fps . . . . . | 2700.0 |
|----------------------------|--------|

#### 4.6 Transearth Coast

In the transearth phase continuous MSFN coverage is available from the time the spacecraft appears from behind the moon until about 2 minutes prior to entry interface (table X). Guam is the last station to track prior to entry. The spacecraft remains in sunlight during the transearth coast phase until entering the earth umbra approximately 26 minutes prior to entry interface:

|  |             |
|--|-------------|
| Return equatorial inclination, deg . . . . . | 23.7        |
| Time from TEI to entry, hr:min . . . . .     | 92:57       |
| Entry interface, hr:min:sec g.e.t. . . . .   | 230:40:33.0 |

#### 4.7 Reentry

The reentry phase of the reference trajectory was simulated with the Apollo Reentry Simulation (ARS) program in six-degrees-of-freedom. Three-degrees-of-freedom trajectories were used to determine the CM maneuver footprint. The reentry corridor is presented in figure 6.

At the nominal EI,  $230^{\text{h}}40^{\text{m}}33^{\text{s}}$  after lift-off, the CM is at an altitude of 400 487 ft and the coordinates are  $172.48^{\circ}$  E longitude and  $14.069^{\circ}$  N geodetic latitude. Inertial velocity, flight-path angle, and azimuth at this point are 36 052 fps,  $6.48^{\circ}$  below the local horizontal, and  $70.68^{\circ}$ , respectively.

Figure 7 shows a plot of the CM maneuver footprint and the nominal ground trace on a map of the reentry area. The footprint is extended out to a 3500-n. mi. reentry range. The nominal touchdown target location is 1350-n. mi. down range from the reentry interface position, and the coordinates of the target are  $165^{\circ}$  W longitude and  $20.55^{\circ}$  N geodetic latitude. Table X gives a sequence of pertinent events, including the periods of communication blackout which occur along the trajectory. Figure 8, which shows altitude as a function of range to the target, denotes the guidance phases. Time histories of the bank angle commanded by the guidance system, load factor, and altitude are presented in figure 9. The load factor at the c.g. reaches a first maximum of  $6.19g$  and a second maximum of  $5.67g$ . Figure 10 shows the time histories of the total heating rate and the total heat load. The maximum total heating rate is  $276.0 \text{ B.t.u./ft}^2/\text{sec}$  and the total heat load is  $26\ 331 \text{ B.t.u./ft}^2$ . Time histories of velocity and flight-path angle, both inertial and relative, are presented in figures 11(a) and 11(b).

The CM RCS uses 11.55 lb of propellant for the separation and attitude hold maneuvers prior to 400 000 ft. The RCS then uses 17.26 lb of propellant to perform the guidance commands during the remainder of the reentry. Figure 12 shows a time history of the total RCS fuel consumption. In figure 13, the altitude is presented as a function of relative velocity, and the boundaries for S-band and C-band communication blackout are shown (ref. 16). Figure 14 shows the time histories of the primary DSKY displays, commanded bank angle, altitude rate, and inertial velocity.

The drogue parachute deployment sequence starts at an altitude of 23 300 ft,  $8\frac{3}{32}$  s after EI. Two seconds later, the two drogue parachutes are deployed. At an altitude of 10 500 ft, the low altitude baroswitch closes, and the drogue parachutes are disconnected. One second after the baroswitch closes, the three main parachutes are deployed. The CM, suspended on the main parachutes, reaches splashdown  $14\frac{1}{6}$  s after EI. The relative velocity and relative flight-path angle versus time are plotted in figure 15 from drogue chute deployment. Figure 16 shows load factor and altitude versus time from drogue chute deployment.

An EMS scroll (non-exit pattern) is presented in figure 17(a) with the reference trajectory from 0.05g superimposed upon it. This pattern has limit lines which allow the crew to monitor the reentry trajectory to prevent the spacecraft from exiting the atmosphere ( $g < 0.2$ ). The commanded bank angle and EMS range-to-go versus the inertial velocity are plotted in figure 17(b).

TABLE I.- SPACECRAFT WEIGHT SUMMARY<sup>a</sup>

|  | Weight, lb |        |
|--|------------|--------|
|  | Component  | Totals |
| Command Module: Inert (including crew and RCS propellant . . . |            | 12 920 |
| Service Module:  |            |        |
| SM inert <sup>b</sup> . . . . .                                | 10 800     |        |
| SPS usable propellant . . . .                                  | 38 815     |        |
| SPS unusable propellant . . . .                                | 885        |        |
| Total . . . . .  |            | 50 500 |
| Lunar Module:  |            |        |
| Descent stage inert <sup>c</sup> . . . . .                     | 4 590      |        |
| Descent stage propellant (usable) . . . . .                    | 17 513     |        |
| Ascent stage inert <sup>d</sup> . . . . .                      | 4 861      |        |
| Ascent stage propellant (usable) . . . . .                     | 5 044      |        |
| RCS (usable) . . . . .   | 588        |        |
| Total . . . . .  |            | 32 596 |

<sup>a</sup>Reference 17.<sup>b</sup>Includes 202 lb of unusable SPS propellant, 1300 lb of usable RCS propellant, and 60 lb of unusable RCS propellant.<sup>c</sup>Includes 286 lb of unusable DPS propellant.<sup>d</sup>Includes 68 lb of unusable APS propellant and 45 lb of undeliverable RCS propellant.

TABLE I.- SPACECRAFT WEIGHT SUMMARY<sup>a</sup> - Concluded

|  | Weight, lb |         |
|--|------------|---------|
|  | Component  | Totals  |
| Adapter:   |            |         |
| Spacecraft-LM adapter . . . . .                                | 3 776      |         |
| Spacecraft-LM adapter ring . . .                               | 91         |         |
| Total . . . . . . . . . . .                                    |            | 3 867   |
| Total for spacecraft at TLI . . . . .                          |            | 100 000 |
| Weight transferred to LM . . . . .                             | 474        |         |
| LM separated weight <sup>e</sup> . . . . .                     | 33 033     |         |
| Weight transferred back to CSM . . .                           | 596        |         |
| Spacecraft inert weight prior to<br>CM-SM separation . . . . . | 23 925     |         |

<sup>a</sup>Reference 17.<sup>b</sup>Includes 202 lb of unusable SPS propellant, 1300 lb of usable RCS propellant, and 60 lb of unusable RCS propellant.<sup>c</sup>Includes 286 lb of unusable DPS propellant.<sup>d</sup>Includes 68 lb of unusable APS propellant and 45 lb of undeliverable RCS propellant.<sup>e</sup>Includes 20 lb of consumables which are used between CSM/LM separation and DOI.

TABLE II.- ENGINE PERFORMANCE SUMMARY

## (a) Service module

| Propulsion system | $I_{sp}$ , sec | Thrust per engine, lb | Flow rate per engine, lb/sec |
|-------------------|----------------|-----------------------|------------------------------|
| SPS               | 314.6          | 20 000                | 63.57                        |
| RCS               | 276            | 100                   | 0.362                        |

## (b) Lunar module

| Propulsion system | $I_{sp}$ , sec | Thrust per engine, lb | Percent relative throttle | Flow rate per engine, lb/sec |
|-------------------|----------------|-----------------------|---------------------------|------------------------------|
| DPS <sup>a</sup>  | 293 - 301.1    | 1200 - 6615           | 11.4 - 63                 | 4.1 - 22.0                   |
| DPS <sup>b</sup>  | 302.9          | 9760                  | 93                        | 32.2                         |
| APS               | 304            | 3628                  |                           | 11.93                        |
| RCS               | 273            | 100                   |                           | 0.367                        |

<sup>a</sup>Throttle region.<sup>b</sup>Fixed throttle setting.

TABLE III.- LM BRAKING GATES

| Range<br>gate | Range<br>rate,<br>fps | RCS thrust          |                  |
|---------------|-----------------------|---------------------|------------------|
|               |                       | $\Delta V$ ,<br>fps | Duration,<br>sec |
| 1 n. mi.      | 15                    | 17.2                | 15.3             |
| 1000 ft       | 5                     | 9.6                 | 8.6              |
| 300 ft        | .25                   | 4.6                 | 4.1              |

TABLE IV.- COMMAND MODULE MASS PROPERTIES

CM weight, lb

|                             |    |       |
|-----------------------------|----|-------|
| Entry . . . . .             | 12 | 850.0 |
| Main chute deploy . . . . . | 12 | 303.0 |
| Splashdown . . . . .        | 11 | 618.0 |

Centers of gravity in Apollo coordinate system, in

|                          |   |       |
|--------------------------|---|-------|
| X <sub>A</sub> . . . . . | 1 | 041.2 |
| Y <sub>A</sub> . . . . . |   | -0.1  |
| Z <sub>A</sub> . . . . . |   | 5.7   |

Moments of inertia, slug-ft<sup>2</sup>

|                           |      |
|---------------------------|------|
| I <sub>XX</sub> . . . . . | 6017 |
| I <sub>YY</sub> . . . . . | 5322 |
| I <sub>ZZ</sub> . . . . . | 4790 |

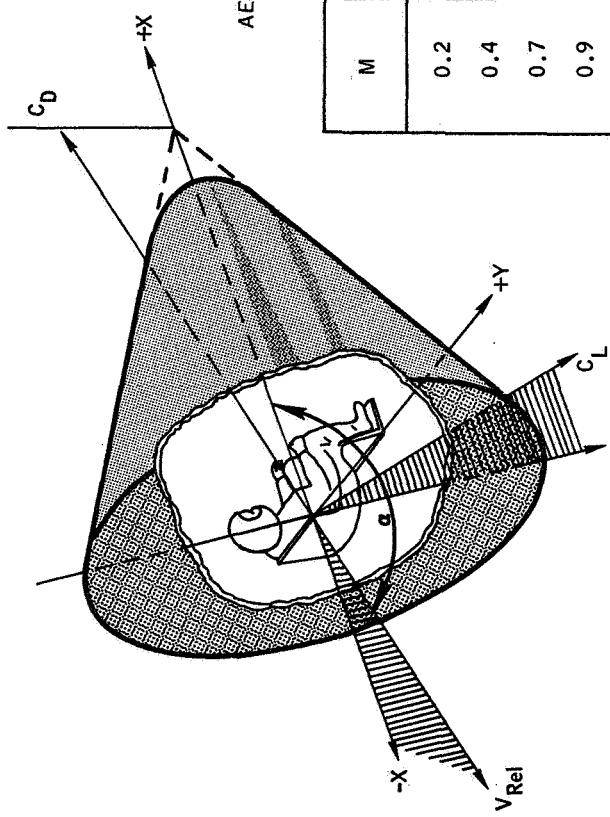
Products of inertia, slug-ft<sup>2</sup>

|                           |        |
|---------------------------|--------|
| I <sub>XY</sub> . . . . . | 51.3   |
| I <sub>XZ</sub> . . . . . | -437.8 |
| I <sub>YZ</sub> . . . . . | 42.6   |

TABLE V.- CONDITIONS AT ENTRY INTERFACE AND TARGET POINT

|  |           |
|--|-----------|
| Elapsed time from launch, hr:min:sec . . . . . | 230:40:33 |
| Inertial velocity, fps . . . . .               | 36 052    |
| Inertial flight-path angle, deg . . . . .      | -6.48     |
| Inertial azimuth, deg . . . . .                | 70.68     |
| Spacecraft geodetic latitude, deg N . . . . .  | 14.069    |
| Spacecraft longitude, deg E . . . . .          | 172.48    |
| Altitude, ft . . . . .                         | 400 487   |
| Target geodetic latitude, deg N . . . . .      | 20.55     |
| Target longitude, deg W . . . . .              | 165       |

TABLE VI.- COMMAND MODULE AERODYNAMIC COEFFICIENTS



AERODYNAMIC COEFFICIENTS AT TRIM ANGLE OF ATTACK  
AS A FUNCTION OF MACH NUMBER

| M    | $\alpha_r$ , deg | $c_L$   | $c_D$   | L/D     |
|------|------------------|---------|---------|---------|
| 0.2  | 171.09           | 0.2275  | 0.8268  | 0.27515 |
| 0.4  | 167.89           | 0.22878 | 0.85565 | 0.26737 |
| 0.7  | 165.32           | 0.25273 | 0.99066 | 0.25511 |
| 0.9  | 162.64           | 0.30696 | 1.0717  | 0.28641 |
| 1.1  | 156.14           | 0.4737  | 1.1845  | 0.39991 |
| 1.2  | 156.25           | 0.46117 | 1.1698  | 0.39424 |
| 1.35 | 155.08           | 0.5254  | 1.2998  | 0.40426 |
| 1.65 | 154.26           | 0.53353 | 1.2639  | 0.42213 |
| 2.0  | 154.24           | 0.52684 | 1.3017  | 0.40473 |
| 2.4  | 154.82           | 0.50076 | 1.2728  | 0.39345 |
| 3.0  | 155.23           | 0.46798 | 1.2397  | 0.3775  |
| 4.0  | 157.09           | 0.43015 | 1.2323  | 0.34905 |
| 10.0 | 157.7            | 0.41711 | 1.2423  | 0.33575 |
| 29.5 | 161.02           | 0.37456 | 1.3075  | 0.28648 |

TABLE VII.- TARGET LOADS FOR NOMINAL POWERED MANEUVERS

(a) Lunar orbit insertion

Propulsion system: SPS

Guidance: External  $\Delta V$ 

## TARGET

|                               |              |
|-------------------------------|--------------|
| $T_{ig}$ , hr:min:sec, g.e.t. | 76:27:46.054 |
| $\Delta V_x$ , fps            | -2962.8724   |
| $\Delta V_y$ , fps            | -277.2619    |
| $\Delta V_z$ , fps            | 5.3296       |
| Weight at $T_{ig}$ , lb       | 94 833.024   |

## REFSMMAT

$$\begin{bmatrix} 0.11152182 & -0.78650429 & -0.60743221 \\ -0.15859187 & 0.58932567 & -0.79217666 \\ 0.98102573 & 0.18467879 & -0.059001051 \end{bmatrix}$$

GIMBAL ANGLES AT  $T_{ig}$ 

|          |     |
|----------|-----|
| IGA, deg | 0.0 |
| MGA, deg | 0.0 |
| OGA, deg | 180 |

TABLE VII.- TARGET LOADS FOR NOMINAL POWERED MANEUVERS - Continued

(b) Lunar parking orbit circularization

Propulsion system: SPS

Guidance: External  $\Delta V$ 

## TARGET

|                               |              |
|-------------------------------|--------------|
| $T_{ig}$ , hr:min:sec, g.e.t. | 80:54:23.560 |
| $\Delta V_X$ , fps            | -138.9599    |
| $\Delta V_Y$ , fps            | 0.0          |
| $\Delta V_Z$ , fps            | 0.9374       |
| Weight at $T_{ig}$ , lb       | 70 656.911   |

## REFSMMAT

$$\begin{bmatrix} -0.18722486 & -0.87290052 & -0.45054583 \\ -0.11476193 & 0.47495213 & -0.87249653 \\ 0.97559038 & -0.11164753 & -0.18909859 \end{bmatrix}$$

GIMBAL ANGLES AT  $T_{ig}$ 

|          |     |
|----------|-----|
| IGA, deg | 0.0 |
| MGA, deg | 0.0 |
| OGA, deg | 180 |

TABLE VII.- TARGET LOADS FOR NOMINAL POWERED MANEUVERS - Continued

## (c) Descent orbit insertion maneuver

Propulsion system: DPS (SE = -1), mass = 1026.2 slugs

Guidance: external  $\Delta V$ 

## TARGET

|                              |              |
|------------------------------|--------------|
| $T_{ig}$ , hr:min:sec g.e.t. | 98:11:57.328 |
| $\Delta V_X$ , fps           | -70.06       |
| $\Delta V_Y$ , fps           | 0            |
| $\Delta V_Z$ , fps           | - .39        |
| Weight at $T_{ig}$ , lb      | 33 013       |

## REFSMMAT

$$\begin{bmatrix} .45647065 & .80678168 & .37515049 \\ .11656396 & -.47223334 & .87373253 \\ .88206996 & -.35510422 & -.30960233 \end{bmatrix}$$

GIMBAL ANGLES AT  $T_{ig}$ 

|           |        |
|-----------|--------|
| IIGA, deg | -72.33 |
| MGA, deg  | 0      |
| OGA, deg  | -180   |

TABLE VII.— TARGET LOADS FOR NOMINAL POWERED MANEUVERS – Continued

| (d) Powered descent     |   |   |   |
|-------------------------|---|---|---|
| Phase duration, sec     | Ignition <sup>a</sup>                         | Braking <sup>b</sup>  | Approach and landing  |
| Ullage ( $T_u$ ) = 7.5  | $RIGXG = -130566.5 \text{ (ft)}$              | Position, ft  | Position, ft  |
| Trim ( $T_t$ ) = 26.0   | $RIGZG = -1413159.7 \text{ (ft)}$             | $ROFG(1) = 77.133$<br>$ROFG(2) = 0.0$<br>$ROFG(3) = -1.733$ | $RIFG(1) = 77.133$<br>$RIFG(2) = 0.0$<br>$RIFG(3) = -1.733$ |
| Braking = 470.0         | $VIGG = 5575.22 \text{ (fps)}$                |   |   |
| Approach = 154.0        | $K_X = .6176310 \text{ (ft/ft)}$              | Velocity, fps   | Velocity, fps   |
| Vertical descent = 20.0 | $K_Y = .755 \times 10^{-6} \text{ (ft/ft}^2)$ | $VOFG(1) = -7.1$<br>$VOFG(2) = 0.0$<br>$VOFG(3) = 1.3$      | $VIFG(1) = -3.1$<br>$VIFG(2) = 0.0$<br>$VIFG(3) = 1.3$      |
|                         | $K_V = 410 \text{ (ft/fps)}$                  | Acceleration, $\text{ft/sec}^2$                             | Acceleration, $\text{ft/sec}^2$                             |
|                         |   | $AOFG(1) = .20$<br>$AOFG(2) = 0.0$<br>$AOFG(3) = -.65$      | $AIFG(1) = .05$<br>$AIFG(2) = 0.0$<br>$AIFG(3) = -.65$      |
|                         |   | $JOFG(3) = .034336$   | $JIFG(3) = .045636$   |
|                         |   | Tend BRAK = 160.0 sec                                       | Tend APPR = 10.0 sec  |

<sup>a</sup>Gimbal angles at  $T_{ig}$  (ftp)

IGA, deg . . . . . 103.93  
 MGA, deg . . . . . -.15  
 OGA, deg . . . . . 180.00

<sup>b</sup> $T_{ig}$ , (ftp), hr:min:sec g.e.t. 99:09:54.17

TABLE VII.- TARGET LOADS FOR NOMINAL POWERED MANEUVERS - Continued

(e) Lunar orbit plane change

Propulsion system: SPS

Guidance: External  $\Delta V$ 

## TARGET

|                               |               |
|-------------------------------|---------------|
| $T_{ig}$ , hr:min:sec, g.e.t. | 118:29:14.484 |
| $\Delta V_X$ , fps            | 0.0           |
| $\Delta V_Y$ , fps            | -150.0449     |
| $\Delta V_Z$ , fps            | 0.0           |
| Weight, lb                    | 36 339.469    |

## REFSMMAT

$$\begin{bmatrix} -0.11736098 & 0.47161820 & -0.87395807 \\ 0.27491570 & 0.86107611 & 0.42774911 \\ 0.95427868 & -0.19006374 & -0.23071198 \end{bmatrix}$$

GIMBAL ANGLES AT  $T_{ig}$ 

|          |     |
|----------|-----|
| IGA, deg | 0.0 |
| MGA, deg | 0.0 |
| OGA, deg | 180 |

TABLE VII.— TARGET LOADS FOR NOMINAL POWERED MANEUVERS — Continued

(f) Powered ascent

Propulsion system: APS

Guidance: ascent guidance

## TARGET

|   |               |
|---|---------------|
| $T_{ig}$ (lift-off), hr:min:sec g.e.t. . . . . . . . . .      | 121:00:44.795 |
| $R_D$ (desired injection radius), ft . . . . . . . . .        | 5 757 424.6   |
| $Y_D$ (desired injection cross-range distance), ft . . . .    | 0.0           |
| $R_D$ (desired injection radial velocity), fps . . . . .      | 0.0           |
| $Y_D$ (desired injection cross-range velocity), fps . . . .   | 0.0           |
| $Z_D$ (down-range velocity for desired injection), fps .      | 5 512.585     |
| Weight at $T_{ig}$ , lb . . . . . . . . . . . . . . . . . . . | 10 736.3      |

REFSMMAT

$$\begin{bmatrix} 0.27033752 & 0.87434928 & 0.40302724 \\ 0.12529564 & -0.44700508 & 0.88571297 \\ 0.95457773 & -0.18894390 & -0.23039440 \end{bmatrix}$$

### GIMBAL ANGLES AT $T_{ig}$

TABLE VII.- TARGET LOADS FOR NOMINAL POWERED MANEUVERS - Continued

| (g) CSI  |             |
|--|-------------|
| Propulsion system: RCS   |             |
| Guidance: external $\Delta V$  |             |
| TARGET   |             |
| $T_{ig}$ , hr:min:sec g.e.t.   | 122:02:15.9 |
| $\Delta V_X$ , fps   | 48.6        |
| $\Delta V_Y$ , fps   | 0           |
| $\Delta V_Z$ , fps   | 0           |
| Weight at $T_{ig}$ , lb  | 5807.0      |
| REFSMMAT   |             |
| $\begin{bmatrix} .27033752 & .87434928 & .40302724 \\ .12529564 & -.44700507 & .88571296 \\ .95457772 & -.18894389 & -.23039439 \end{bmatrix}$ |             |
| GIMBAL ANGLES AT $T_{ig}$  |             |
| IGA, deg   | 174.2       |
| MGA, deg   | 0.0         |
| OGA, deg   | 0.0         |

TABLE VII.- TARGET LOADS FOR NOMINAL POWERED MANEUVERS - Continued

(h) CDH

Propulsion system: RCS

Guidance: external  $\Delta V$

## TARGET

|                         |   |             |
|-------------------------|---|-------------|
| $T_{ig}$ , hr:min:sec   | g.e.t. . . . .                            | 122:59:49.7 |
| $\Delta V_X$ , fps      | · | 21.0        |
| $\Delta V_Y$ , fps      | · | 0.0         |
| $\Delta V_Z$ , fps      | · | -4.9        |
| Weight at $T_{ig}$ , lb | · | 5775.0      |

REFSMMAT

|           |            |            |
|-----------|------------|------------|
| .27033752 | .87434928  | .40302724  |
| .12529564 | -.44700507 | .88571296  |
| .95457772 | -.18894389 | -.23039439 |

### GIMBAL ANGLES AT T<sub>ig</sub>

|          |       |      |
|----------|-------|------|
| IGA, deg | ..... | -6.5 |
| MGA, deg | ..... | 0.0  |
| OGA, deg | ..... | 0.0  |

TABLE VII.— TARGET LOADS FOR NOMINAL POWERED MANEUVERS - Continued

(i) TPI

Propulsion system: RCS

Guidance: Lambert

## TARGET

REFSMMAT

|           |            |            |
|-----------|------------|------------|
| .27033752 | .87434928  | .40302724  |
| .12529564 | -.44700507 | .88571296  |
| .95457772 | -.18894389 | -.23039439 |

### GIMBAL ANGLES AT $T_{ig}$

TABLE VII.— TARGET LOADS FOR NOMINAL POWERED MANEUVERS - Continued

(j) Transearth injection

Propulsion system: SPS

Guidance: External  $\Delta V$

## TARGET

|  |               |
|--|---------------|
| $T_{ig}$ , hr:min:sec, g.e.t. . . . . . . . . . . . . . . . . .          | 137:43:30.199 |
| $\Delta V_X$ , fps . | 2696.5110     |
| $\Delta V_Y$ , fps . | -124.6240     |
| $\Delta V_Z$ , fps . | -56.2425      |
| Weight at $T_{ig}$ , lb .    | 36 220.664    |

REFSMMAT

$$\begin{bmatrix} 0.27033752 & 0.87434928 & 0.40302724 \\ 0.12529564 & -0.44700507 & 0.88571296 \\ 0.95457772 & -0.18894389 & -0.23039439 \end{bmatrix}$$

### GIMBAL ANGLES AT $T_{ig}$

|          |      |
|----------|------|
| IGA, deg | 96.4 |
| MGA, deg | -2.6 |
| OGA, deg | -0.0 |

TABLE VII.- TARGET LOADS FOR NOMINAL POWERED MANEUVERS - Concluded

(k) Entry

## REFSMMAT

|            |             |             |
|------------|-------------|-------------|
| -0.4138778 | 0.093811666 | -0.9054858  |
| 0.85185502 | 0.39066450  | -0.34889007 |
| 0.32101119 | -0.91574048 | -0.24160130 |

## GIMBAL ANGLES AT EI

|                    |      |
|--------------------|------|
| IGA, deg . . . . . | 156. |
| MGA, deg . . . . . | 0.0  |
| OGA, deg . . . . . | 0.0  |

TABLE VIII.- MISSION RADAR TIMELINE FOR LM DESCENT PHASE

[From undocking to touchdown]

| Station        | Acquisition         |                 |                  | Termination         |                 |                  |
|----------------|---------------------|-----------------|------------------|---------------------|-----------------|------------------|
|                | Time,<br>hr:min:sec | Azimuth,<br>deg | Range,<br>n. mi. | Time,<br>hr:min:sec | Azimuth,<br>deg | Range,<br>n. mi. |
| Guam           | 96:55:44            | 110             | 207 475          | 98:07:18            | 120             | 206 631          |
| Carnarvon      | 96:55:48            | 98              | 208 760          | 98:07:19            | 92              | 207 734          |
| Canberra       | 96:55:54            | 75              | 207 092          | 98:07:24            | 61              | 206 395          |
| Hawaii         | 96:55:55            | 179             | 206 227          | 98:07:29            | -153            | 206 258          |
| Goldstone      | 96:56:01            | -131            | 207 445          | 98:07:36            | -118            | 207 998          |
| Guaymas        | 96:56:05            | -122            | 207 433          | 98:07:39            | -112            | 208 095          |
| Corpus         | 96:56:07            | -114            | 207 998          | 98:07:40            | -105            | 208 753          |
| Merritt Island | 96:56:09            | -105            | 208 831          | 97:16:12            | -103            | 208 070          |
| Grand Bahama   | 96:56:10            | -103            | 208 930          | 97:07:58            | -102            | 208 455          |
| Guam           | 98:56:30            | 131             | 205 990          | (a)                 | --              | --               |
| Carnarvon      | 98:56:31            | 87              | 206 887          | (a)                 | --              | --               |
| Canberra       | 98:56:37            | 46              | 205 848          | (a)                 | --              | --               |
| Hawaii         | 98:56:38            | -137            | 206 256          | (a)                 | --              | --               |
| Goldstone      | 98:56:38            | -110            | 208 271          | (a)                 | --              | --               |
| Guaymas        | 98:56:44            | -106            | 208 432          | (a)                 | --              | --               |

<sup>a</sup>Stations still tracking at touchdown

TABLE IX.- RENDEZVOUS MANEUVER SUMMARY

| Maneuver          | G.e.t.<br>at ignition,<br>day:hr:min:sec | $\Delta V$ ,<br>fps | Duration,<br>sec | Resultant<br>orbit<br>$h_a/h_p$ ,<br>n. mi. | RCS<br>thruster<br>usage | Range<br>at cutoff,<br>n. mi. | Range rate<br>at cutoff,<br>fps |
|-------------------|--|---------------------|------------------|---|--------------------------|-------------------------------|---------------------------------|
| CSI               | 5:02:02:15.9                             | 48.6                | 43.7             | 44.3/28.5                                   | +Z (2-jet)               | 174.60                        | -266.8                          |
| CDH               | 5:02:59:49.7                             | 21.7                | 19.4             | 44.6/43.4                                   | +Z (2-jet)               | 72.90                         | -121.8                          |
| TPI               | 5:03:34:12.6                             | 25.3                | 22.6             | 60.2/43.9                                   | +Z (2-jet)               | 32.70                         | -135.2                          |
| First<br>braking  | 5:04:14:02.7                             | 17.2                | 15.3             | 58.9/51.5                                   | -Z (2-jet)               | 0.94                          | -15.3                           |
| Second<br>braking | 5:04:19:37.9                             | 9.6                 | 8.6              | 58.6/56.9                                   | -Z (2-jet)               | 0.15                          | -4.8                            |
| Third<br>braking  | 5:04:21:55.2                             | 4.6                 | 4.1              | 59.8/58.5                                   | -Z (2-jet)               | 0.05                          | -0.2                            |

TABLE X.- TRANSEARTH COAST RADAR TIMELINE

## (a) Definitions of radar table headings

|        |                            |
|--------|----------------------------|
| MLA CB | Merritt Island C-band      |
| PAT CB | Patrick C-band             |
| KEN CB | Cape Kennedy C-band        |
| GBI CB | Grand Bahama Island C-band |
| GTI CB | Grand Turk Island C-band   |
| BDA CB | Bermuda C-band             |
| ANT CB | Antigua C-band             |
| CYI CB | Grand Canary C-band        |
| ASC CB | Ascension Island C-band    |
| PRE CB | Pretoria C-band            |
| CAR CB | Carnarvon C-band           |
| HAW CB | Hawaii C-band              |
| CAL CB | Pt. Arguello C-band        |
| WHS CB | White Sands C-band         |
| EGL CB | Eglin C-band               |
| TAN TM | Tananarive telemetry       |
| KNO TM | Kano telemetry             |
| MLA SB | Merritt Island S-band      |
| GBI SB | Grand Bahama Island S-band |
| BDA SB | Bermuda S-band             |
| ANT SB | Antigua S-band             |
| CYI SB | Grand Canary S-band        |

TABLE X.-- TRANSEARTH COAST RADAR TIMELINE - Continued

## (a) Definitions of radar table headings - Concluded

|        |                      |
|--------|----------------------|
| ASC SB | Ascension S-band     |
| CAR SB | Carnarvon S-band     |
| GUM SB | Guam S-band          |
| HAW SB | Hawaii S-band        |
| GYM SB | Guaymas S-band       |
| TEX SB | Corpus S-band        |
| MAD DS | Madrid deep space    |
| CNB DS | Canberra deep space  |
| GLD DS | Goldstone deep space |
| SHIP 1 | Insertion ship       |
| SHIP 2 | Injection ship (1)   |
| SHIP 3 | Injection ship (2)   |

TABLE X.- TRANSEARTH COAST RADAR TIMELINE - Continued.

(b) 0° minimum elevation angle  
 [TEI cutoff,  $5^{\text{d}} \cdot h_4 \cdot \bar{h}_4 \cdot g \cdot e.t.$ ]

## VEHICLE 1 RADAR TABLE

## TRACKING TIME

|        | STATION ACQUISITION DATA |     |     |     |     |     | STATION TERMINATION DATA |      |     |     |     |     |     |        |     |     |     |     |      |     |      |     |     |     |        |
|--------|--------------------------|-----|-----|-----|-----|-----|--------------------------|------|-----|-----|-----|-----|-----|--------|-----|-----|-----|-----|------|-----|------|-----|-----|-----|--------|
|        | HRS                      | MIN | SEC | DAY | HRs | MIN | SEC                      | RA   | DEC | AZ  | ELV | X   | Y   | RANGE  | DAY | HRs | MIN | SEC | RA   | DEC | AZ   | ELV | X   | Y   | RANGE  |
| GYM SB | 10                       | 5   | 12  | 5   | 18  | 6   | 28                       | -140 | -20 | 115 | 3   | 87  | *25 | 205960 | 6   | 4   | 11  | 40  | -142 | -20 | *113 | 6   | *90 | -21 | 199223 |
| TEX SB | 9                        | 12  | 36  | 5   | 18  | 6   | 28                       | -140 | -20 | 122 | 14  | 74  | *51 | 205335 | 6   | 3   | 19  | 4   | -142 | -20 | *113 | 6   | *90 | -21 | 199864 |
| MLA SB | 8                        | 4   | 0   | 5   | 18  | 6   | 30                       | -140 | -20 | 134 | 25  | 57  | *39 | 204703 | 6   | 2   | 10  | 30  | -142 | -20 | *113 | 6   | *90 | -21 | 210049 |
| GB1 SB | 7                        | 57  | 52  | 5   | 18  | 6   | 30                       | -140 | -20 | 135 | 28  | 53  | *39 | 204549 | 6   | 2   | 4   | 23  | -142 | -20 | *112 | 6   | *90 | -21 | 200659 |
| BDA SB | 6                        | 52  | 5   | 5   | 18  | 6   | 32                       | -140 | -20 | 149 | 31  | 41  | *47 | 204598 | 6   | 0   | 58  | 37  | -142 | -20 | *114 | 0   | *90 | -24 | 201534 |
| ANT SB | 7                        | 7   | 46  | 5   | 18  | 6   | 34                       | -140 | -20 | 145 | 45  | 30  | *35 | 203723 | 6   | 1   | 14  | 22  | -142 | -20 | *111 | 6   | *90 | -21 | 201541 |
| CY1 SB | 3                        | 45  | 20  | 5   | 18  | 6   | 45                       | -141 | -20 | 154 | 38  | 29  | *46 | 204663 | 5   | 21  | 52  | 5   | -142 | -20 | *113 | 0   | *90 | -21 | 203967 |
| MAD DS | 2                        | 31  | 29  | 5   | 18  | 6   | 45                       | -141 | -20 | 147 | 22  | 65  | *31 | 204878 | 5   | 20  | 38  | 14  | -142 | -20 | *117 | 0   | 90  | -63 | 204817 |
| ASC SB | 4                        | 34  | 24  | 5   | 18  | 6   | 53                       | -141 | -20 | 121 | 65  | -22 | *13 | 203664 | 5   | 22  | 41  | 13  | -142 | -19 | *109 | 6   | *90 | -19 | 203464 |
| GLD DS | 9                        | 51  | 16  | 5   | 18  | 29  | 54                       | -140 | -20 | 115 | 0   | 90  | 65  | 203108 | 6   | 4   | 21  | 13  | -142 | -20 | *115 | 0   | 90  | -65 | 199664 |
| HAW SB | 10                       | 44  | 45  | 5   | 20  | 53  | 29                       | -140 | -20 | 112 | 0   | 90  | *22 | 204648 | 6   | 7   | 38  | 14  | -142 | -20 | *117 | 0   | *90 | -21 | 196320 |
| CNB DS | 13                       | 47  | 3   | 5   | 22  | 47  | 54                       | -140 | -19 | 113 | 0   | 90  | 67  | 203299 | 6   | 12  | 34  | 57  | -141 | -19 | *113 | 0   | 90  | -67 | 191645 |
| GUM SB | 11                       | 15  | 43  | 6   | 0   | 21  | 16                       | -140 | -20 | 110 | 0   | 90  | *20 | 202169 | 6   | 11  | 34  | 59  | -141 | -20 | *110 | 0   | *90 | -21 | 192353 |
| CAR SB | 13                       | 7   | 37  | 6   | 1   | 28  | 39                       | -140 | -19 | 111 | 0   | 90  | *21 | 204363 | 6   | 14  | 36  | 16  | -141 | -19 | *111 | 0   | *90 | -21 | 189849 |
| ASC SB | 12                       | 16  | 47  | 6   | 10  | 27  | 44                       | -139 | -19 | 109 | 0   | 90  | *19 | 193843 | 6   | 22  | 44  | 30  | -140 | -20 | *110 | 0   | *90 | -21 | 180924 |
| MAD DS | 9                        | 29  | 7   | 6   | 11  | 10  | 15                       | -139 | -20 | 117 | 0   | 90  | 63  | 193778 | 6   | 20  | 39  | 21  | -140 | -20 | *117 | 0   | 90  | -61 | 183340 |
| CY1 SB | 10                       | 26  | 6   | 6   | 11  | 27  | 37                       | -139 | -20 | 113 | 0   | 90  | *23 | 192902 | 6   | 21  | 54  | 3   | -140 | -20 | *113 | 0   | *90 | -21 | 185912 |
| ANT SB | 11                       | 3   | 29  | 6   | 14  | 14  | 38                       | -139 | -20 | 111 | 0   | 90  | *21 | 192026 | 7   | 1   | 18  | 7   | -140 | -20 | *111 | 0   | *90 | -21 | 177600 |
| BDA SB | 10                       | 7   | 22  | 6   | 14  | 54  | 10                       | -139 | -20 | 114 | 0   | 90  | *24 | 189541 | 7   | 1   | 31  | 31  | -140 | -20 | *114 | 0   | *90 | -24 | 178742 |
| GY1 SB | 10                       | 36  | 10  | 6   | 15  | 37  | 25                       | -139 | -20 | 113 | 0   | 90  | *23 | 188803 | 7   | 2   | 7   | 35  | -140 | -20 | *113 | 0   | *90 | -21 | 176339 |

VEHICLE - 1 RADAR TABLE

TABLE X.- TRANSEARCH COAST RADAR TIMELINE - Continued  
 (b) 0° minimum elevation angle - Continued  
 [TEI cutoff,  $5^{\text{d}} 17^{\text{h}} 45^{\text{m}} 44^{\text{s}}$  g.e.t.]

| TRACKING TIME | STATION ACQUISITION DATA |     |     |     |     |     | STATION TERMINATION DATA |      |     |     |     |     |        |        |   |    |    |      |      |      |      |     |     |        |        |
|---------------|--------------------------|-----|-----|-----|-----|-----|--------------------------|------|-----|-----|-----|-----|--------|--------|---|----|----|------|------|------|------|-----|-----|--------|--------|
|               | HRS                      | MIN | SEC | DAY | HRS | MIN | SEC                      | RA   | DEC | AZ  | ELV | X   | Y      | Z      |   |    |    |      |      |      |      |     |     |        |        |
| MLA SB        | 10                       | 22  | 59  | 6   | 15  | 50  | -139                     | -20  | 113 | 0   | 90  | -23 | 188574 | 7      | 2 | 13 | 49 | -140 | -20  | -113 | 0    | -90 | -23 | 173667 |        |
| TEX SB        | 10                       | 26  | 11  | 6   | 16  | 56  | -139                     | -20  | 113 | 0   | 90  | -23 | 187433 | 7      | 3 | 22 | 32 | -140 | -20  | -113 | 0    | -90 | -23 | 175792 |        |
| GYM SB        | 10                       | 24  | 56  | 6   | 17  | 50  | -139                     | -20  | 113 | 0   | 90  | -23 | 186468 | 7      | 4 | 15 | 30 | -139 | -20  | -113 | 0    | -90 | -23 | 175993 |        |
| GLO DS        | 9                        | 53  | 36  | 6   | 18  | 30  | 53                       | -139 | -20 | 115 | 0   | 90  | 65     | 185738 | 7 | 4  | 24 | 29   | -139 | -21  | -115 | 0   | 90  | -65    | 173793 |
| HAN SB        | 10                       | 46  | 6   | 6   | 20  | 56  | 56                       | -138 | -20 | 112 | 0   | 90  | -22    | 183015 | 7 | 7  | 43 | 2    | -139 | -20  | -112 | 0   | -90 | -22    | 169587 |
| CNB DS        | 13                       | 52  | 58  | 6   | 22  | 51  | 9                        | -138 | -19 | 114 | 0   | 90  | 66     | 180796 | 7 | 12 | 44 | 8    | -138 | -19  | -114 | 0   | 90  | -66    | 161409 |
| GUM SB        | 11                       | 15  | 3   | 7   | 0   | 26  | 21                       | -138 | -20 | 111 | 0   | 90  | -21    | 178870 | 7 | 11 | 41 | 24   | -139 | -20  | -111 | 0   | -90 | -21    | 163316 |
| CAR SB        | 13                       | 12  | 3   | 7   | 1   | 33  | 20                       | -138 | -19 | 111 | 0   | 90  | -21    | 177487 | 7 | 14 | 45 | 23   | -138 | -20  | -112 | 0   | -90 | -22    | 166999 |
| ASC SB        | 12                       | 19  | 22  | 7   | 10  | 55  | 43                       | -136 | -20 | 110 | 0   | 90  | -20    | 165072 | 7 | 22 | 55 | 5    | -137 | -20  | -110 | 0   | -90 | -21    | 144395 |
| MAD DS        | 9                        | 23  | 39  | 7   | 11  | 21  | 35                       | -136 | -21 | 118 | 0   | 90  | 62     | 163915 | 7 | 20 | 45 | 13   | -137 | -21  | -119 | 0   | 90  | -61    | 148514 |
| CY1 SB        | 10                       | 23  | 36  | 7   | 11  | 38  | 11                       | -136 | -21 | 113 | 0   | 90  | -23    | 163496 | 7 | 22 | 1  | 47   | -137 | -21  | -114 | 0   | -90 | -24    | 149889 |
| ANT SB        | 11                       | 2   | 38  | 7   | 14  | 25  | 7                        | -136 | -21 | 112 | 0   | 90  | -22    | 159138 | 8 | 1  | 27 | 46   | -136 | -21  | -112 | 0   | -90 | -23    | 139448 |
| BDA SB        | 10                       | 3   | 35  | 7   | 15  | 6   | 3                        | -136 | -21 | 115 | 0   | 90  | -25    | 158032 | 8 | 1  | 9  | 37   | -136 | -21  | -116 | 0   | -90 | -26    | 139447 |
| GPI SB        | 10                       | 27  | 31  | 7   | 15  | 49  | 5                        | -135 | -21 | 113 | 0   | 90  | -23    | 156856 | 8 | 2  | 16 | 36   | -136 | -21  | -114 | 0   | -90 | -24    | 137712 |
| MLA SB        | 10                       | 19  | 56  | 7   | 16  | 2   | 45                       | -135 | -21 | 114 | 0   | 90  | -24    | 156479 | 8 | 2  | 22 | 41   | -136 | -21  | -114 | 0   | -90 | -24    | 137916 |
| TEX SB        | 10                       | 23  | 16  | 7   | 17  | 8   | 32                       | -135 | -21 | 114 | 0   | 90  | -24    | 154644 | 8 | 3  | 31 | 48   | -136 | -21  | -114 | 0   | -90 | -24    | 135344 |
| GYM SB        | 10                       | 21  | 52  | 7   | 18  | 3   | 12                       | -135 | -21 | 114 | 0   | 90  | -24    | 153084 | 8 | 4  | 25 | 4    | -135 | -21  | -114 | 0   | -90 | -24    | 133301 |
| GLO DS        | 9                        | 46  | 35  | 7   | 18  | 44  | 30                       | -135 | -21 | 116 | 0   | 90  | 64     | 151888 | 8 | 4  | 33 | 5    | -135 | -22  | -117 | 0   | 90  | -64    | 132667 |
| HAN SB        | 10                       | 44  | 17  | 7   | 21  | 10  | 15                       | -134 | -21 | 113 | 0   | 90  | -23    | 147546 | 8 | 7  | 54 | 32   | -135 | -22  | -113 | 0   | -90 | -23    | 125523 |
| CKB DS        | 14                       | 2   | 7   | 7   | 23  | 1   | 20                       | -134 | -20 | 114 | 0   | 90  | 66     | 144101 | 8 | 13 | 3  | 28   | -133 | -20  | -115 | 0   | 90  | -65    | 113227 |

TABLE X.- TRANSHEARTH COAST RADAR TIMELINE - Concluded

(b) 0° minimum elevation angle - Concluded  
 [TEI cutoff,  $\delta_{17}^{d_1} h_{17}^{m_1} l_{17}^{s_1}$  g.e.t.]

## VEHICLE 1 RADAR TABLE

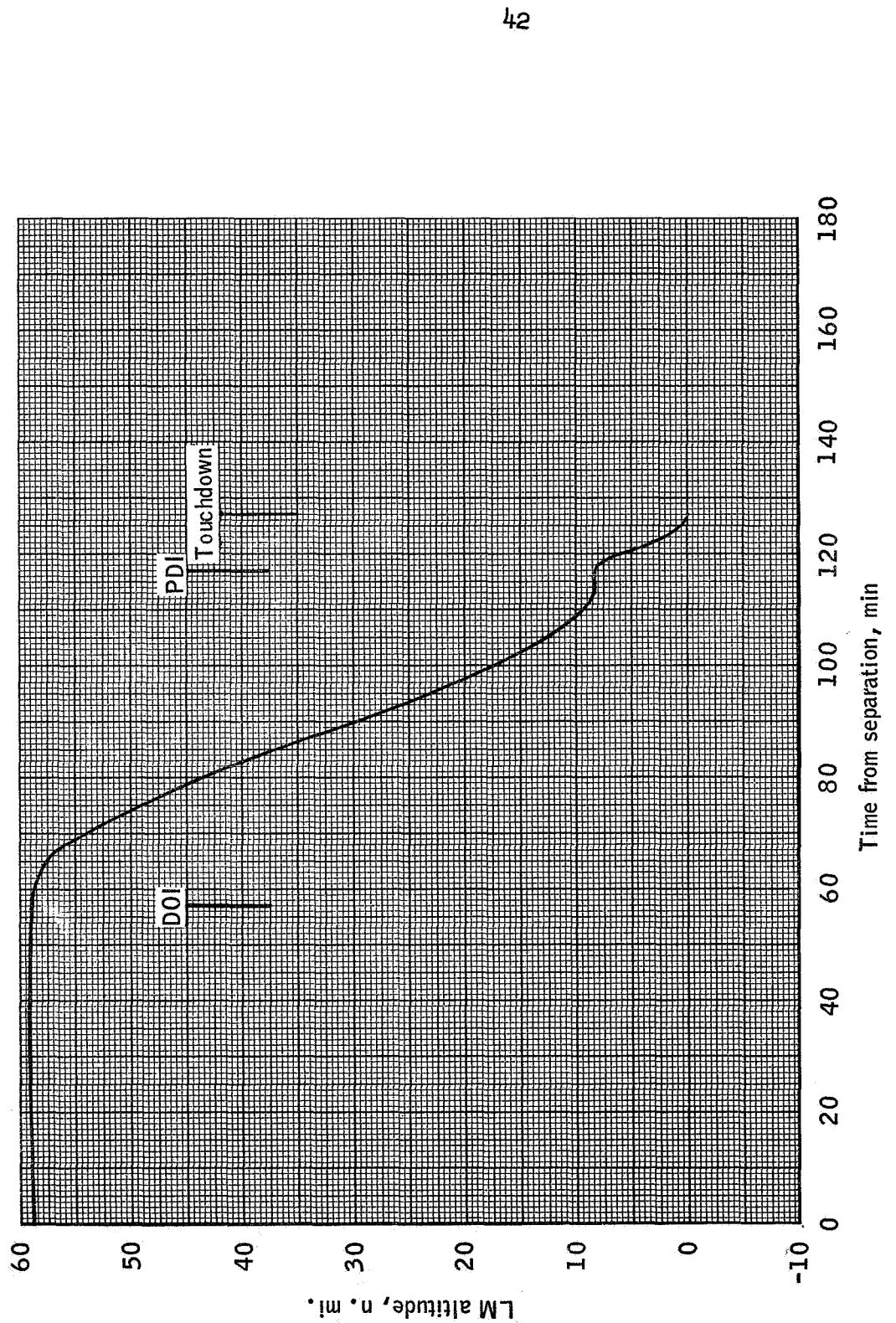
## TRACKING TIME

## STATION ACQUISITION DATA

| VEHICLE | DAY HRS MIN SEC | DAY HRS MIN SEC | RA DEC      | AZ ELV | X      | Y      | RANGE      | DAY HRS MIN SEC | RA DEC | AZ ELV | X    | Y      | RANGE |
|---------|-----------------|-----------------|-------------|--------|--------|--------|------------|-----------------|--------|--------|------|--------|-------|
| GUM SB  | 11 15 13        | 8 0 40          | 31 -133 -21 | 111 0  | 90 -21 | 140906 | 8 11 55    | 43 -134 -22     | 112    | 0 -90  | -25  | 176664 | 40    |
| CAR SB  | 13 19 46        | 8 1 45          | 26 -133 -20 | 112 0  | 90 -22 | 138765 | 8 15 5     | 42 -132 -21     | 113    | 0 -90  | -23  | 167920 |       |
| AGC SB  | 12 27 56        | 8 10 54         | 11 -130 -21 | 111 0  | 90 -21 | 118588 | 8 23 22    | 7 -129 -22      | 112    | 0 -90  | -23  | 13713  |       |
| MAD DS  | 9 14 12         | 8 11 46         | 40 -131 -22 | 120 0  | 90 60  | 116435 | 8 21 0     | 52 -130 -23     | 121    | 0 90   | -50  | 90754  |       |
| CVI SB  | 10 21 2         | 8 12 1          | 10 -130 -22 | 115 0  | 90 -25 | 115836 | 8 22 22    | 12 -129 -23     | 116    | 0 -90  | -24  | 86449  |       |
| ANT SB  | 11 6 3          | 8 14 49         | 22 -129 -22 | 113 0  | 90 -23 | 108619 | 9 1 55     | 26 -127 -23     | 114    | 0 -90  | -24  | 74722  |       |
| BDA SB  | 9 59 30         | 8 15 33         | 28 -129 -22 | 117 0  | 90 -27 | 106643 | 9 1 32     | 58 -127 -24     | 118    | 0 -90  | -28  | 75487  |       |
| GB1 SB  | 10 27 19        | 8 16 16         | 20 -128 -22 | 115 0  | 90 -25 | 104690 | 9 2 43     | 35 -127 -24     | 117    | 0 -90  | -27  | 71725  |       |
| MLA SB  | 10 18 43        | 8 16 30         | 38 -128 -22 | 116 0  | 90 -26 | 10403C | 9 2 49     | 22 -127 -24     | 117    | 0 -90  | -27  | 70760  |       |
| TEX SB  | 10 23 23        | 8 17 37         | 44 -128 -22 | 116 0  | 90 -26 | 100882 | 9 4 1      | 7 -126 -24      | 117    | 0 -90  | -27  | 66501  |       |
| GYM SB  | 10 22 40        | 8 18 33         | 47 -127 -23 | 116 0  | 90 -26 | 98181  | 9 4 56     | 27 -125 -24     | 118    | 0 -90  | -28  | 62447  |       |
| GLD DS  | 9 44 6          | 8 19 17         | 50 -127 -23 | 119 0  | 90 61  | 96008  | 9 5 1      | 56 -124 -25     | 121    | 0 90   | -50  | 61965  |       |
| HAW SB  | 10 56 36        | 8 21 45         | 12 -125 -23 | 115 0  | 90 -25 | 88414  | 9 8 41     | 49 -120 -25     | 117    | 0 -90  | -27  | 15760  |       |
| CNB DS  | 14 59 58        | 8 23 32         | 43 -124 -21 | 116 0  | 90 64  | 82520  | 9 14 32    | 40 -34 51       | 118    | 0 -90  | -18  | 2514   |       |
| GUM SB  | 13 16 14        | 9 1 22          | 24 -122 -23 | 114 0  | 90 -24 | 76126  | 9 14 36    | 38 -81 -8       | 98     | 0 90   | -48  | 1405   |       |
| CAR SB  | 12 7 45         | 9 2 25          | 19 -122 -21 | 113 0  | 90 -23 | 72280  | 9 14 33 4  | 31 36 49        | 0 90   | 47     | 2425 |        |       |
| CAR CB  | 2 37 11         | 9 11 55         | 53 -107 -23 | 92 64  | -26    | 23397  | 9 14 33 4  | 31 36 49        | 0 90   | 47     | 2425 |        |       |
| TAN TM  | 2 16 8          | 9 12 0          | 42 -97 -23  | 104 46 | 43 -10 | 23400  | 9 14 18 50 | -18 -75 95      | 0 90   | -5     | 5979 |        |       |
| PRE CB  | 2 2 58          | 9 12 6          | 52 -95 -22  | 101 30 | 60 -20 | 23400  | 9 14 9 50  | -37 8 99        | 0 90   | -9     | 7375 |        |       |

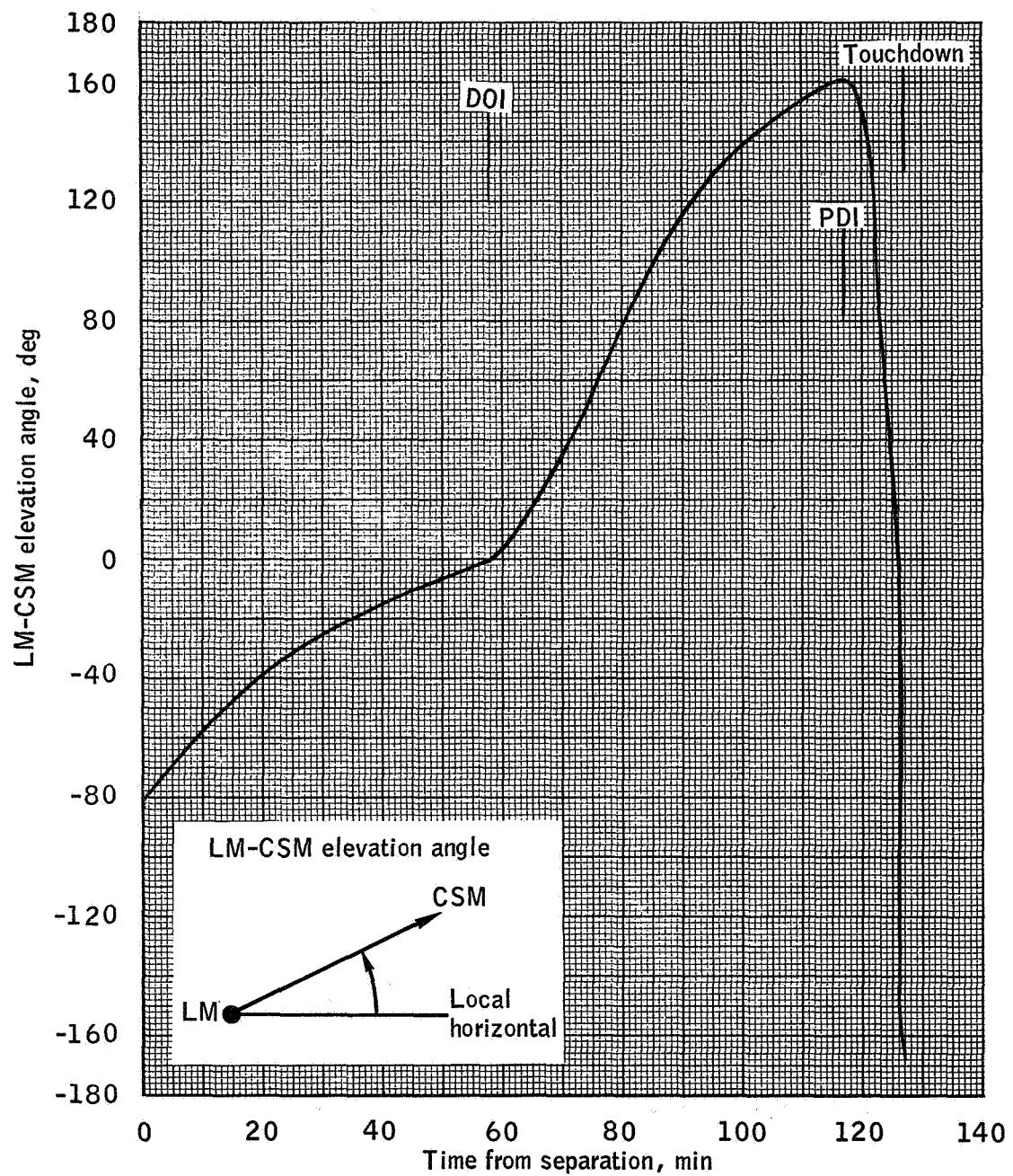
TABLE XI.-- ENTRY EVENTS SEQUENCE

| Event                                | Time from lift-off,<br>hr:min:sec | Time from 400 000 ft,<br>min:sec |
|--------------------------------------|-----------------------------------|----------------------------------|
| Reentry                              | 230:40:33.0                       | 00:00.0                          |
| Enter S-band communication blackout  | 230:40:59.0                       | 00:26.0                          |
| Enter C-band communication blackout  |                                   |                                  |
| Load factor = 0.05g                  | 230:41:03.0                       | 00:30.0                          |
| Maximum heating rate                 | 230:41:43.0                       | 01:10.0                          |
| Guidance initiate at RDOT = -700 fps | 230:41:53.0                       | 01:20.0                          |
| Maximum load factor (first)          | 230:41:57.0                       | 01:24.0                          |
| Enter final phase                    | 230:42:47.0                       | 02:14.0                          |
| Exit C-band communications blackout  | 230:43:37.0                       | 03:04.0                          |
| Exit S-band communications blackout  | 230:44:03.0                       | 03:30.0                          |
| Maximum load factor (second)         | 230:46:23.0                       | 05:50.0                          |
| Termination of CMC guidance          | 230:48:03.0                       | 07:30.0                          |
| Drogue parachute deployment          | 230:49:05.0                       | 08:32.0                          |
| Main parachute deployment            | 230:49:50.6                       | 09:17.6                          |
| Splashdown                           | 230:54:38.6                       | 14:05.6                          |



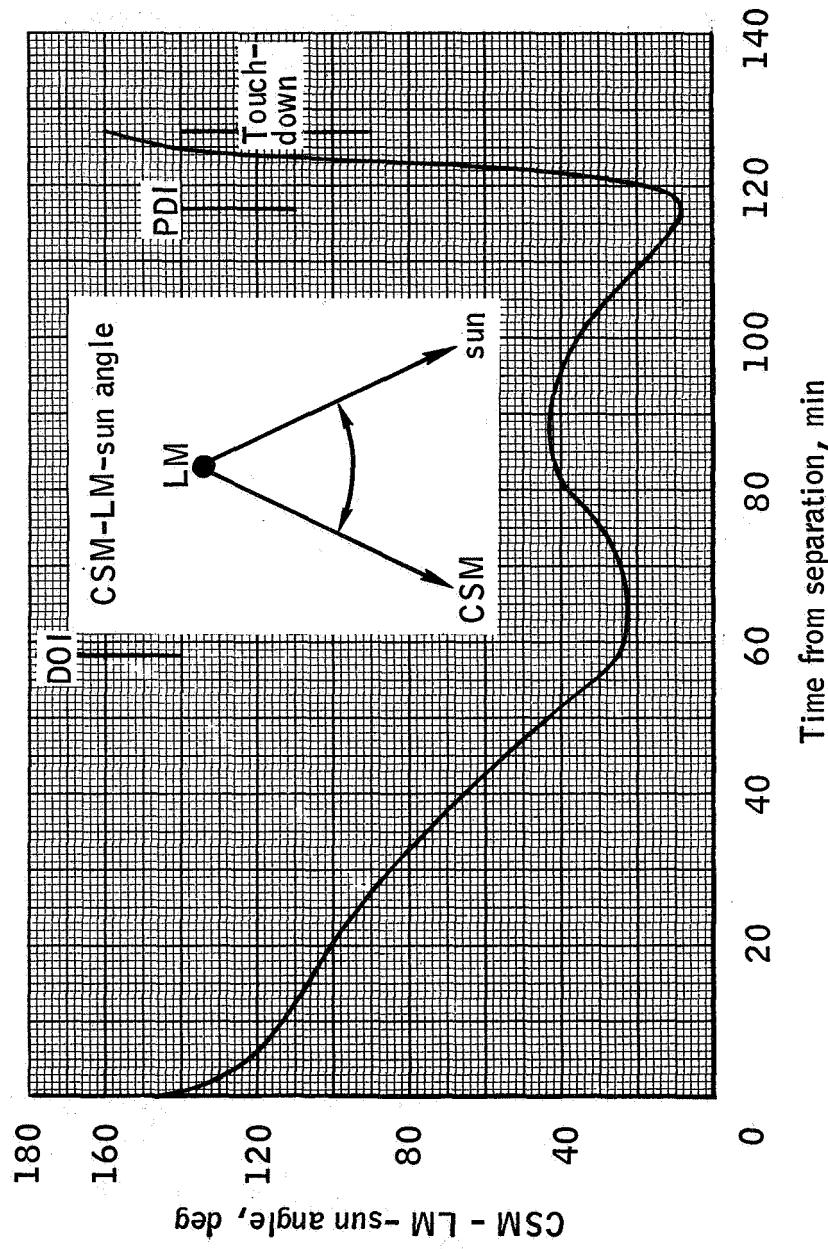
(a) LM altitude versus time from separation.

Figure 1.- CSM and LM trajectory parameters from separation to touchdown.



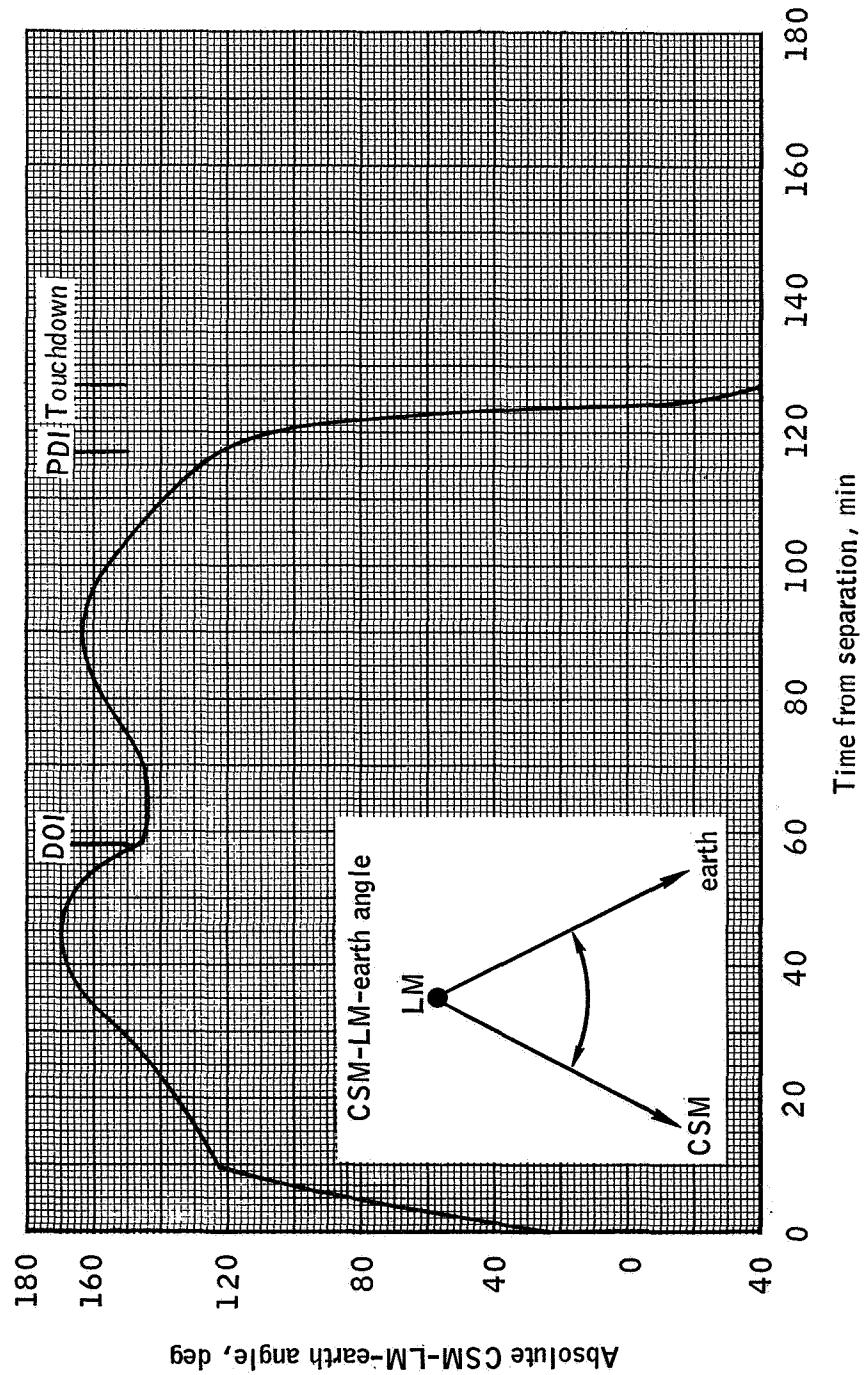
(b) LM-CSM elevation angle versus time from separation.

Figure 1.- Continued.



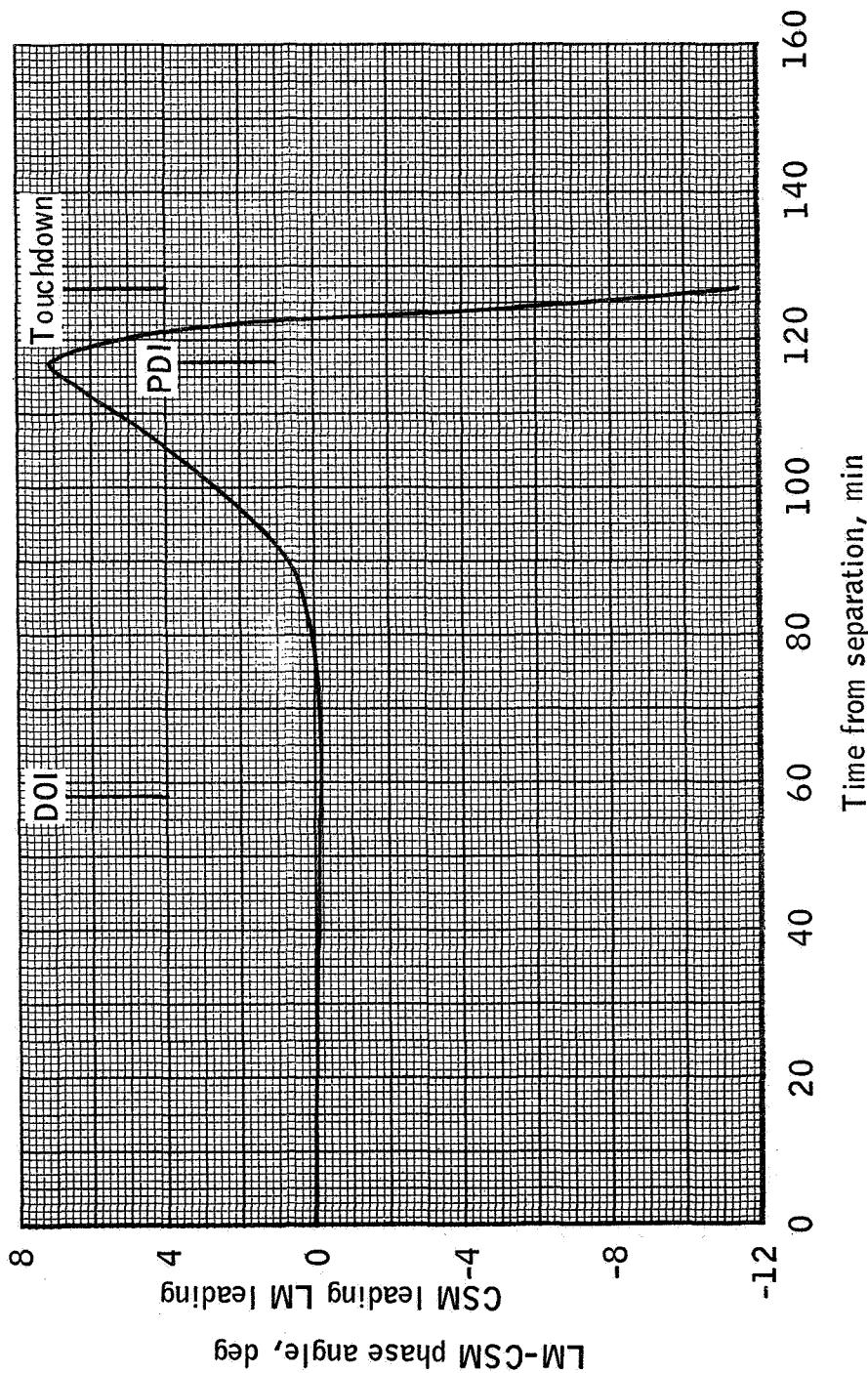
(c) CSM-LM-sun angle versus time from separation.

Figure 1. - Continued.



(d) Absolute CSM-LM-earth angle versus time from separation.

Figure 1.- Continued.



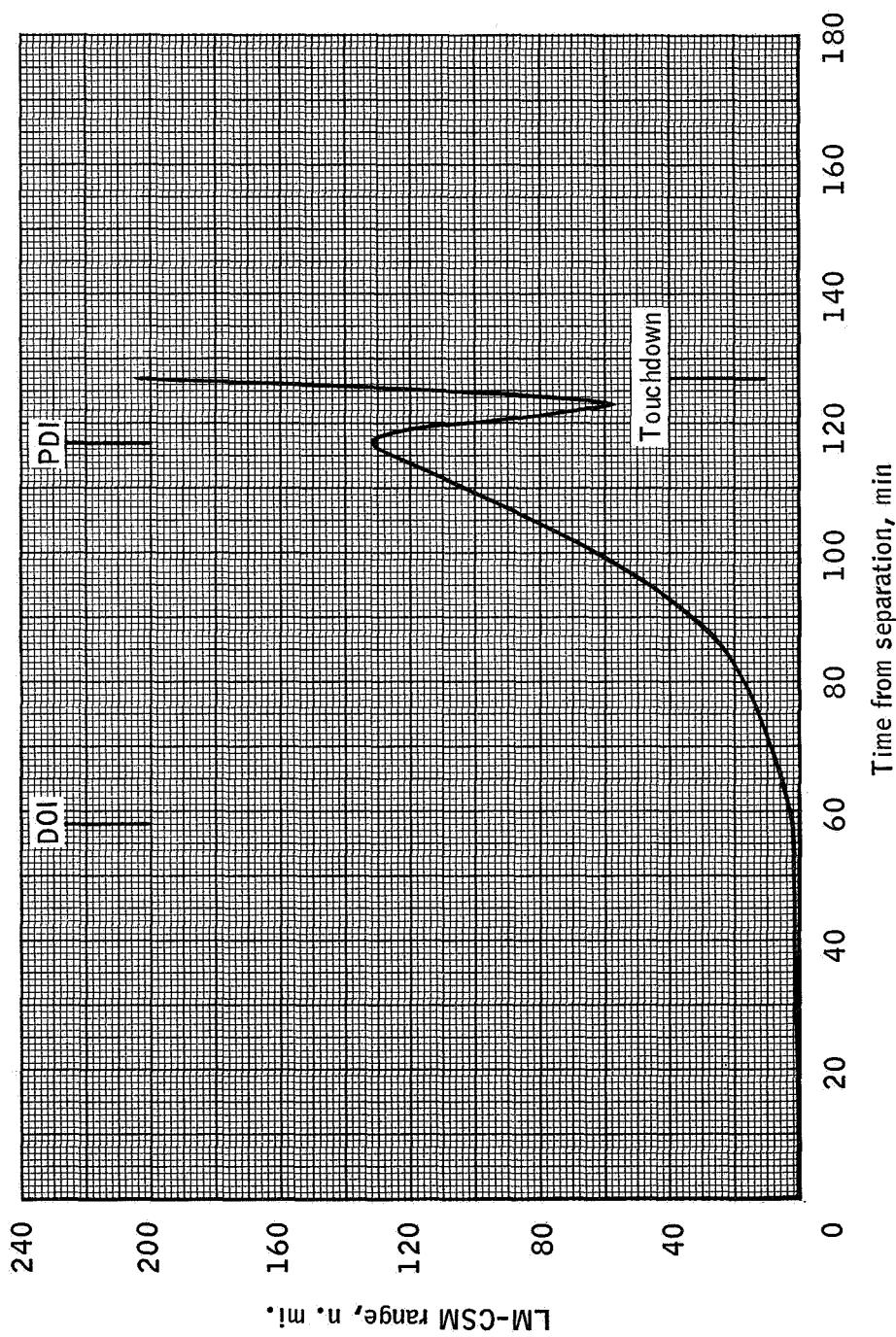
(e) LM-CSM phase angle versus time from separation.

Figure 1.- Continued.



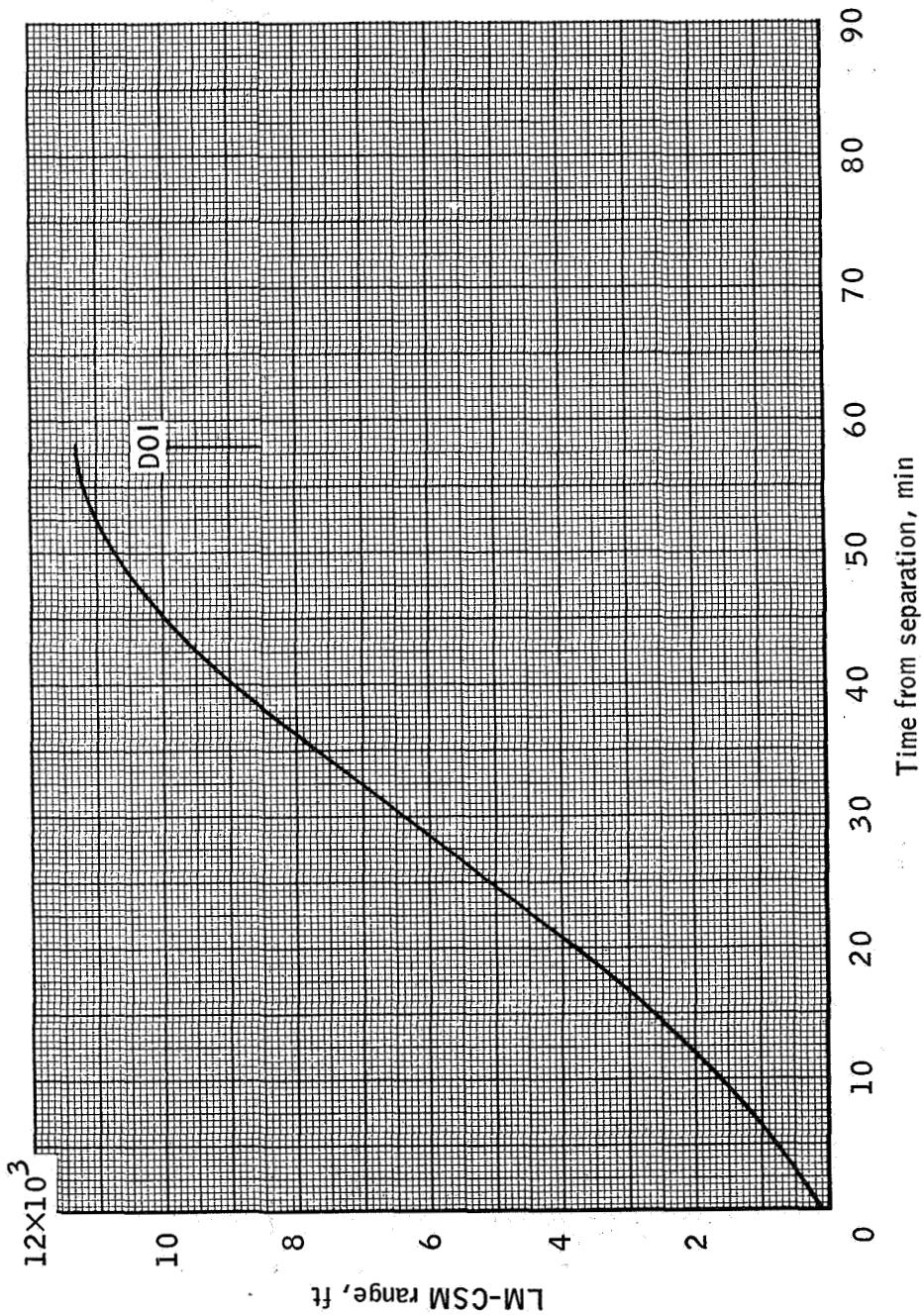
(f) LM-CSM range rate versus time from separation.

Figure 1. – Continued.



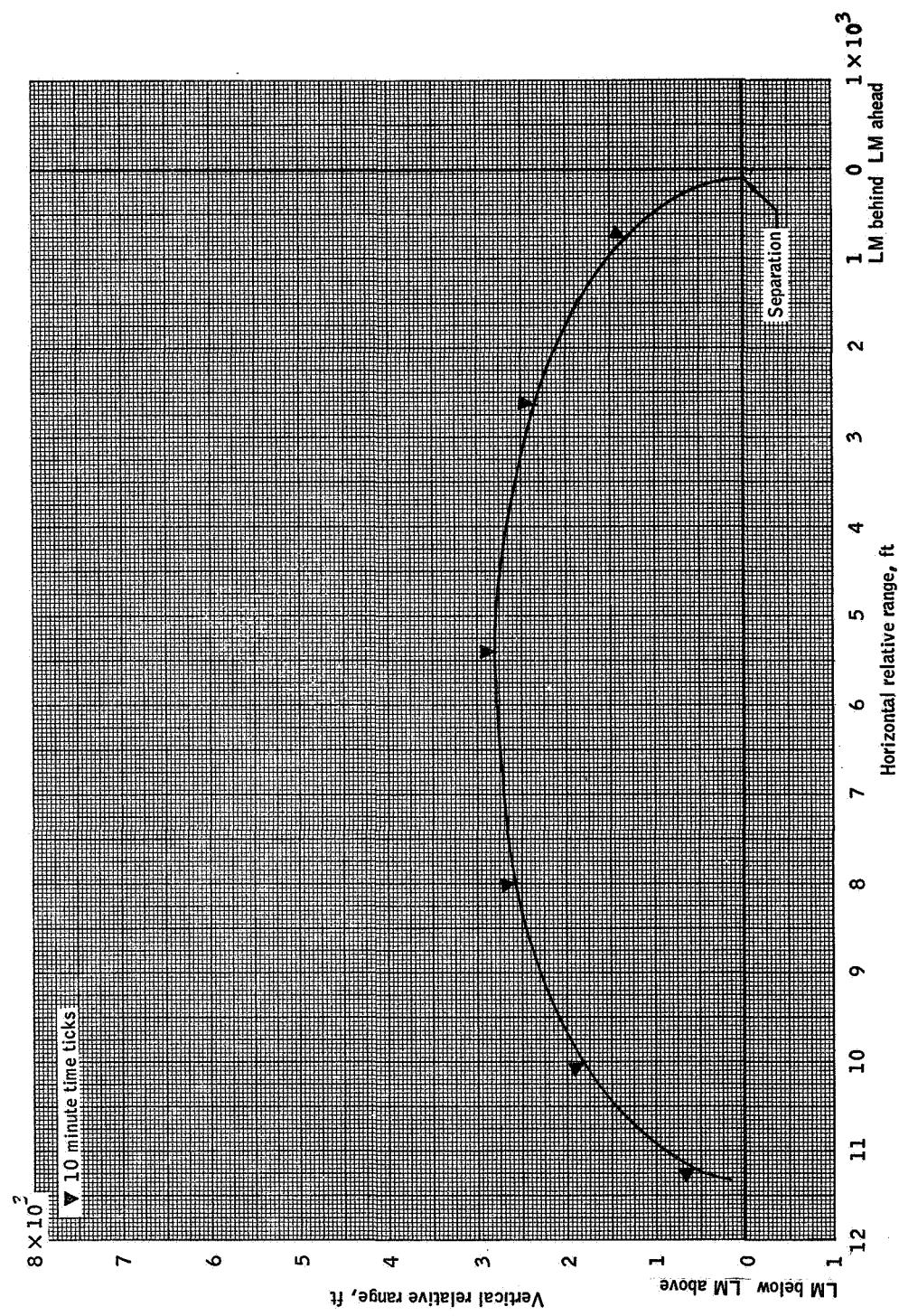
(g) LM-CSM range versus time from separation.

Figure 1.- Continued.



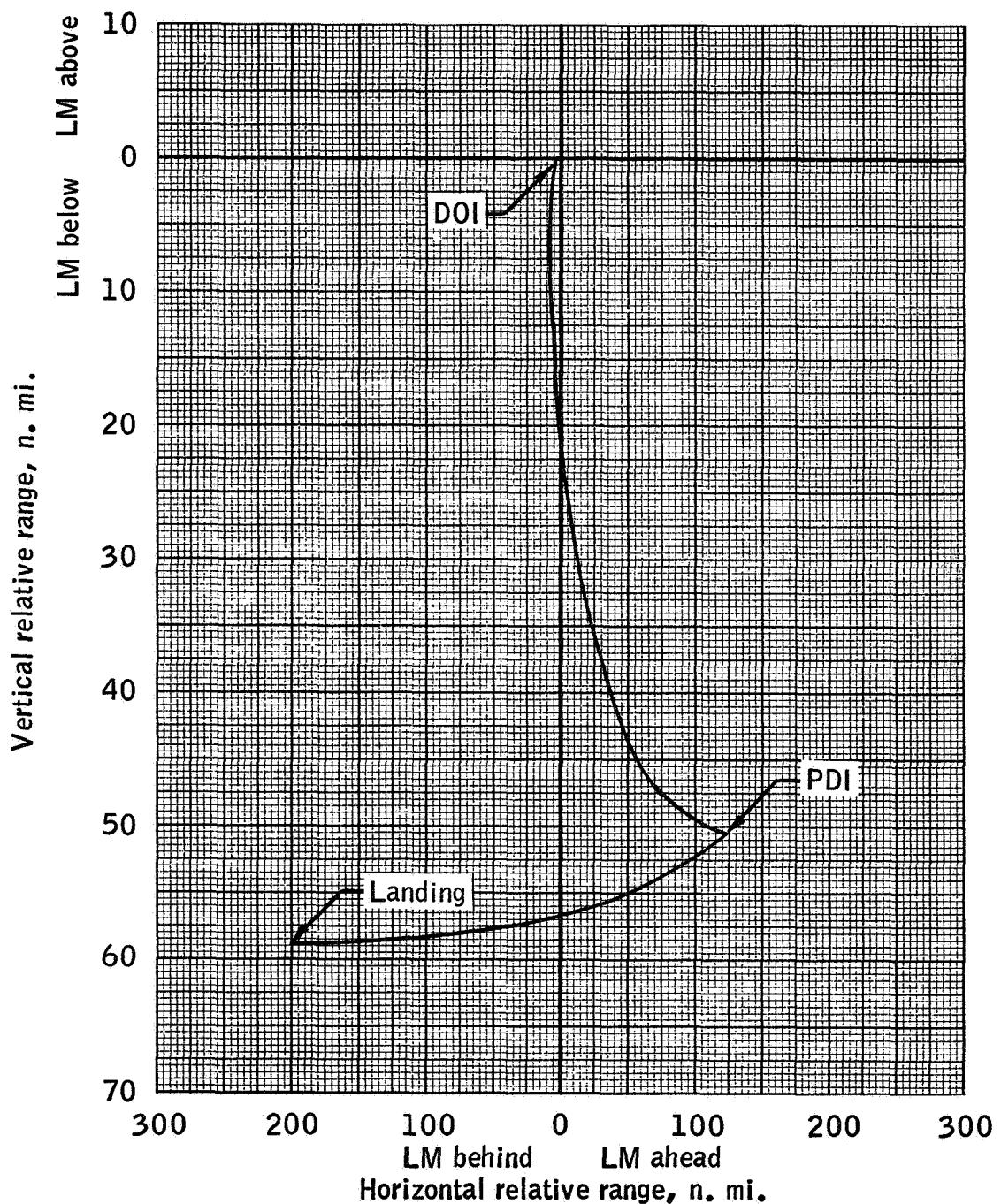
(h) LM-CSM range versus time from separation to DOI.

Figure 1. - Continued.



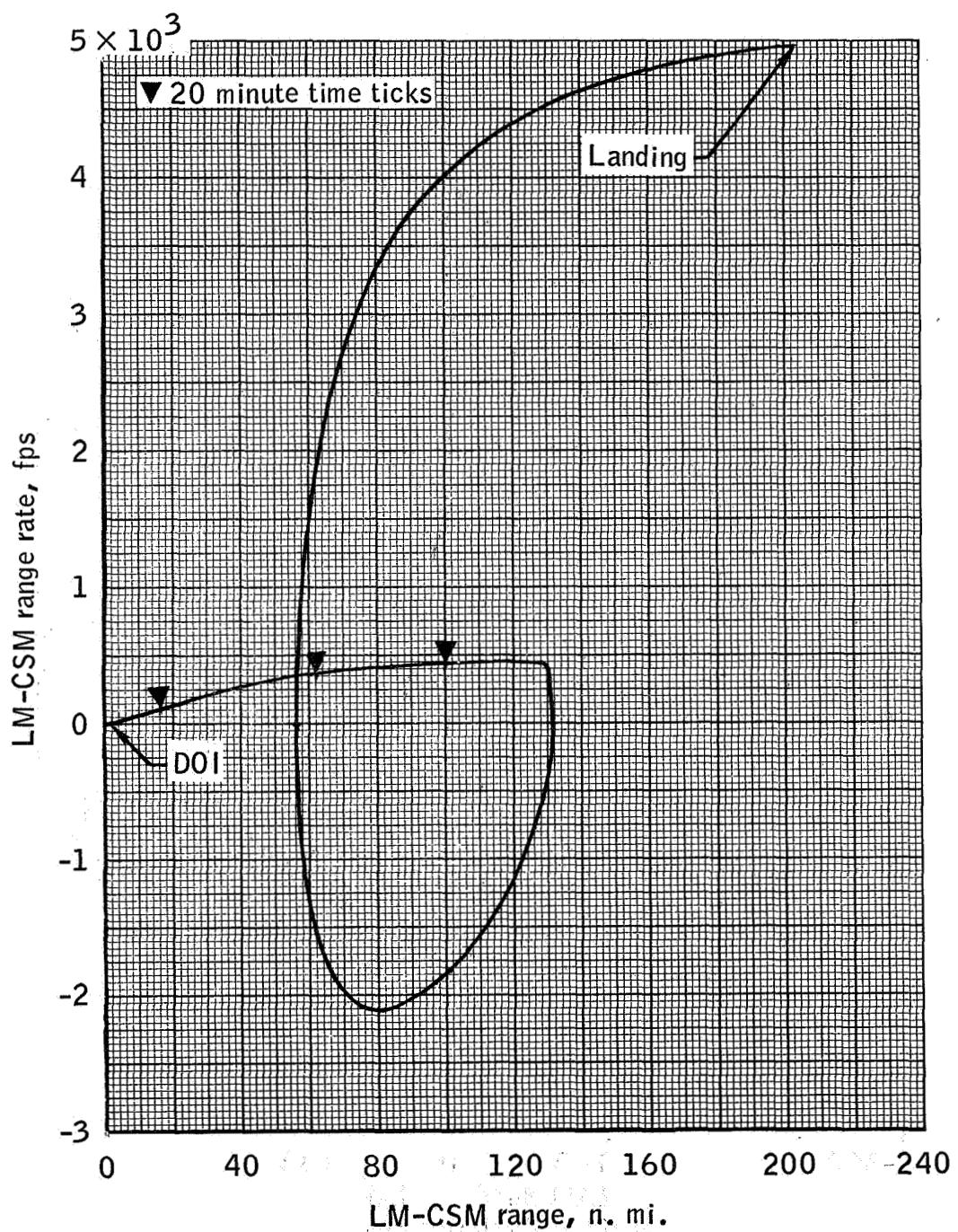
(f) LM-CSM relative motion (CSM centered curvilinear) immediately after separation.

Figure 1.- Continued.



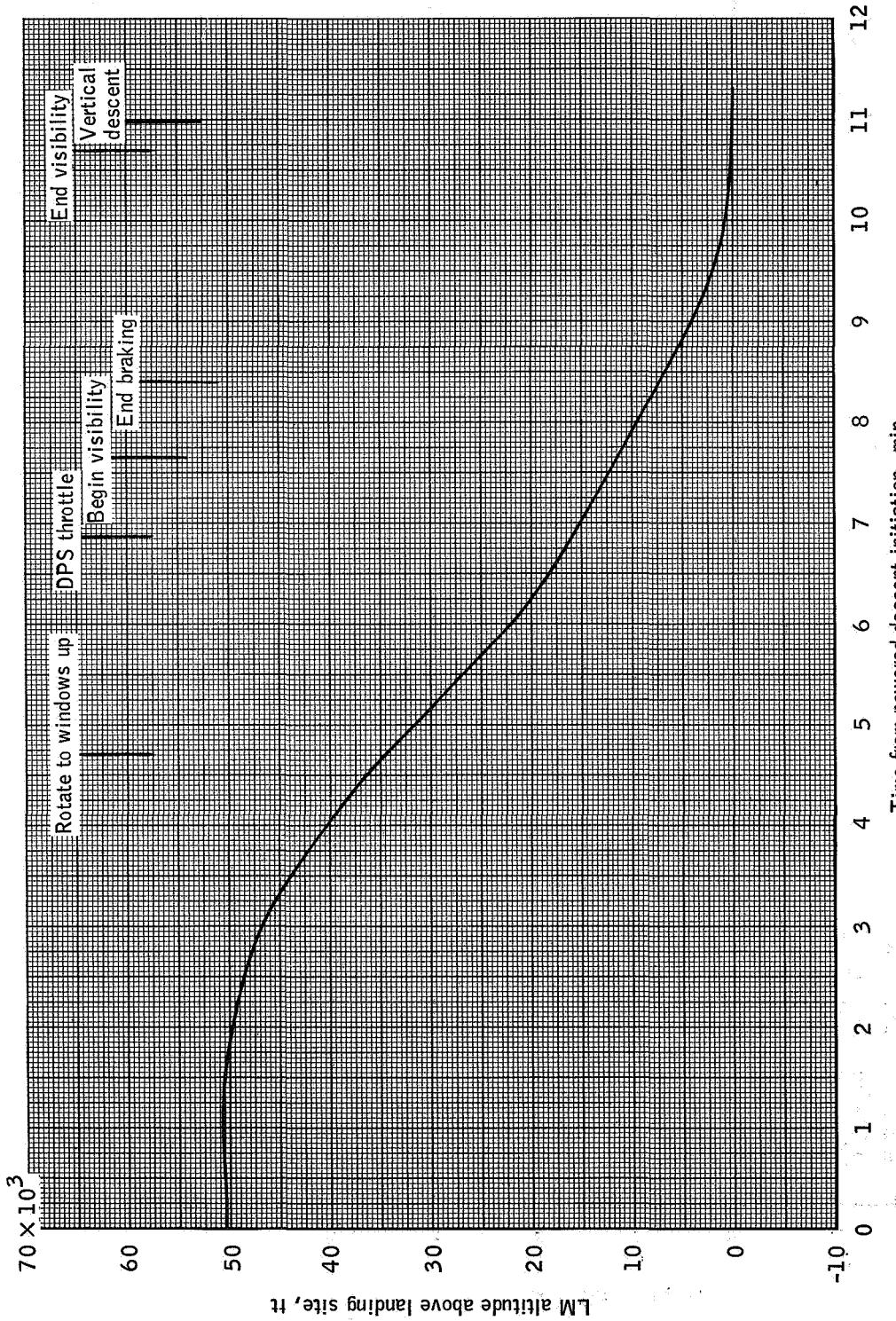
(j) LM-CSM relative motion (CSM centered curvilinear).

Figure 1.- Continued.



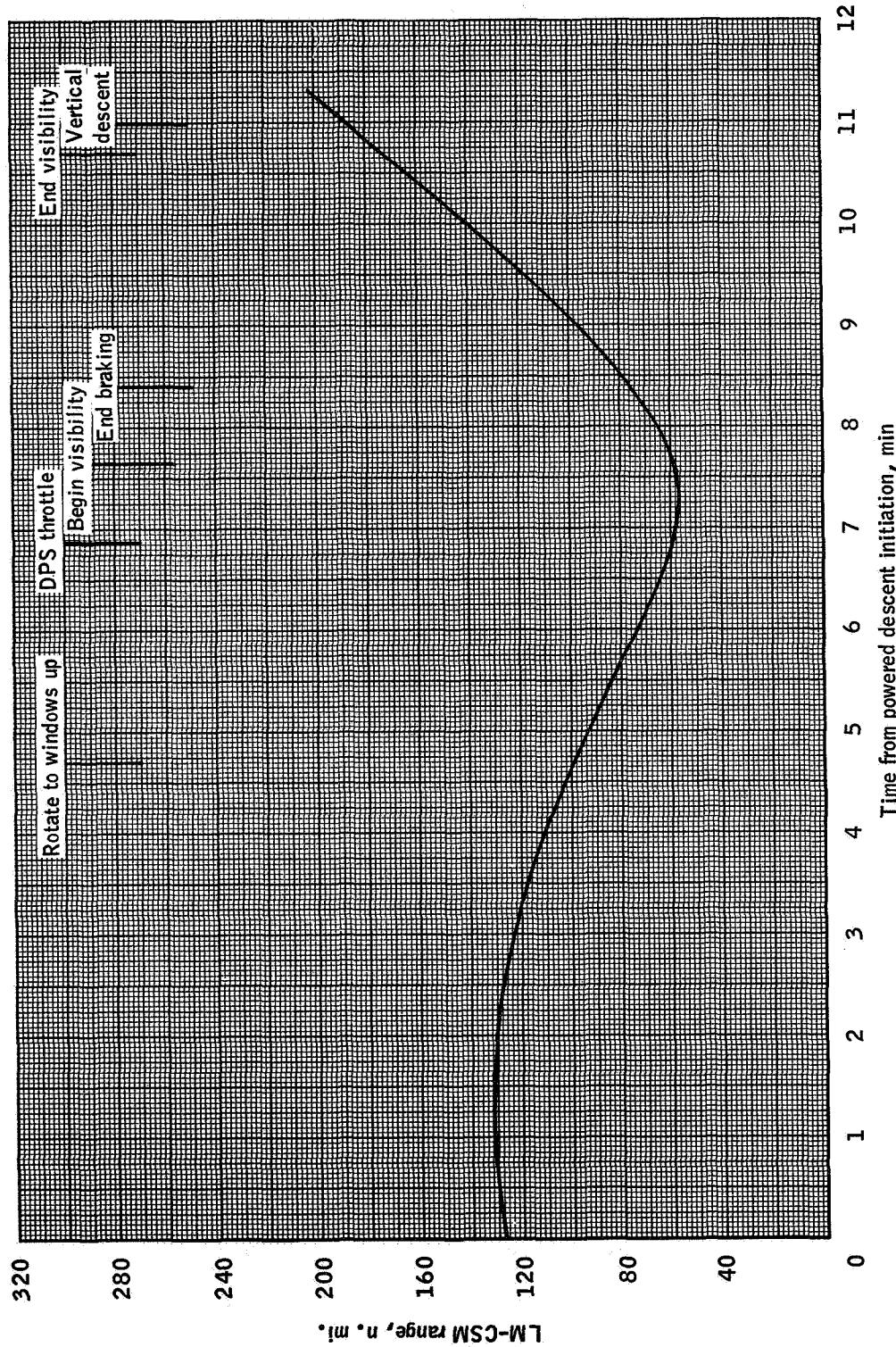
(k) LM-CSM range rate versus range.

Figure 1.- Concluded.



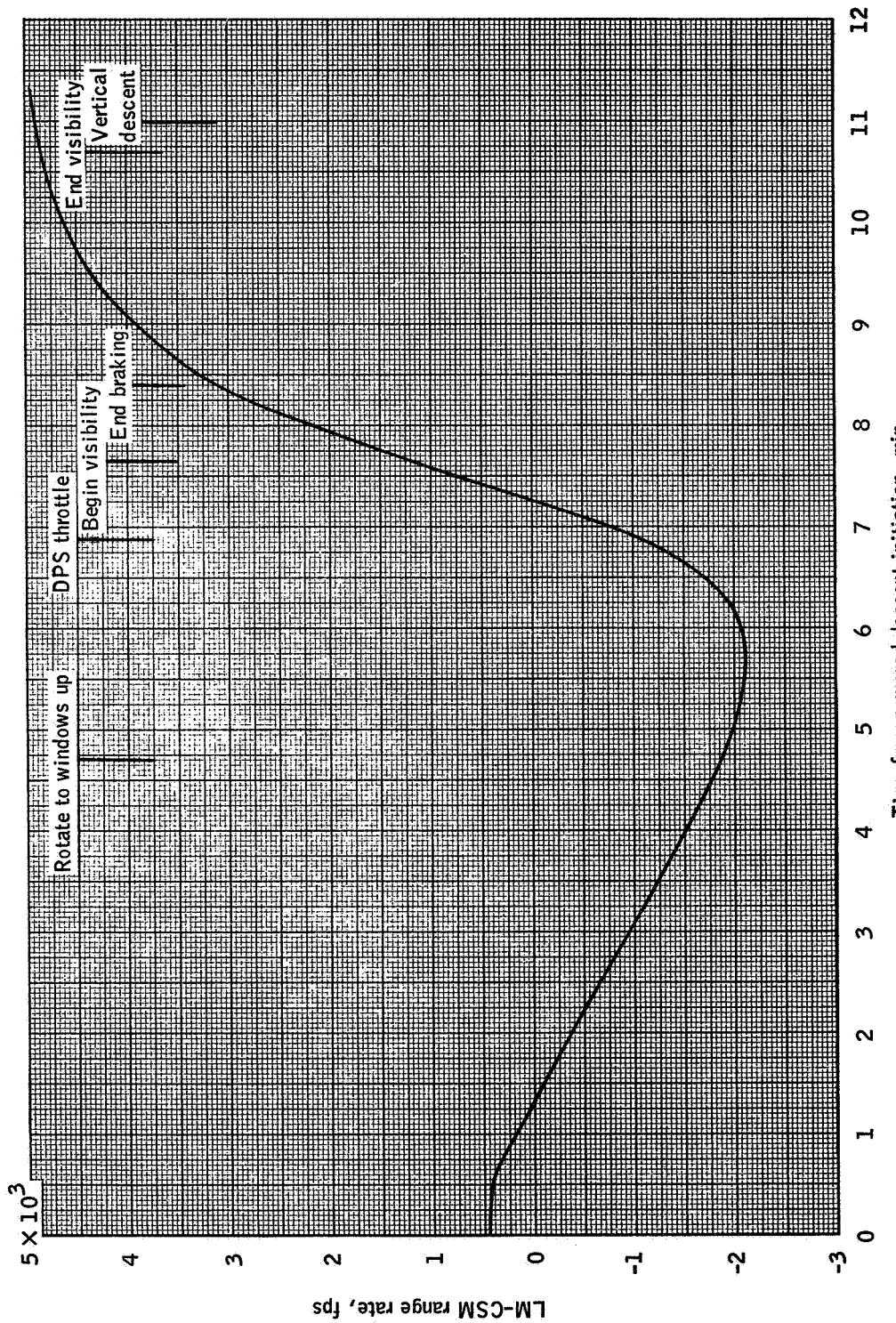
(a) LM altitude above landing site versus time from powered descent initiation.

Figure 2.- LM and CSM trajectory parameters during LM powered descent.



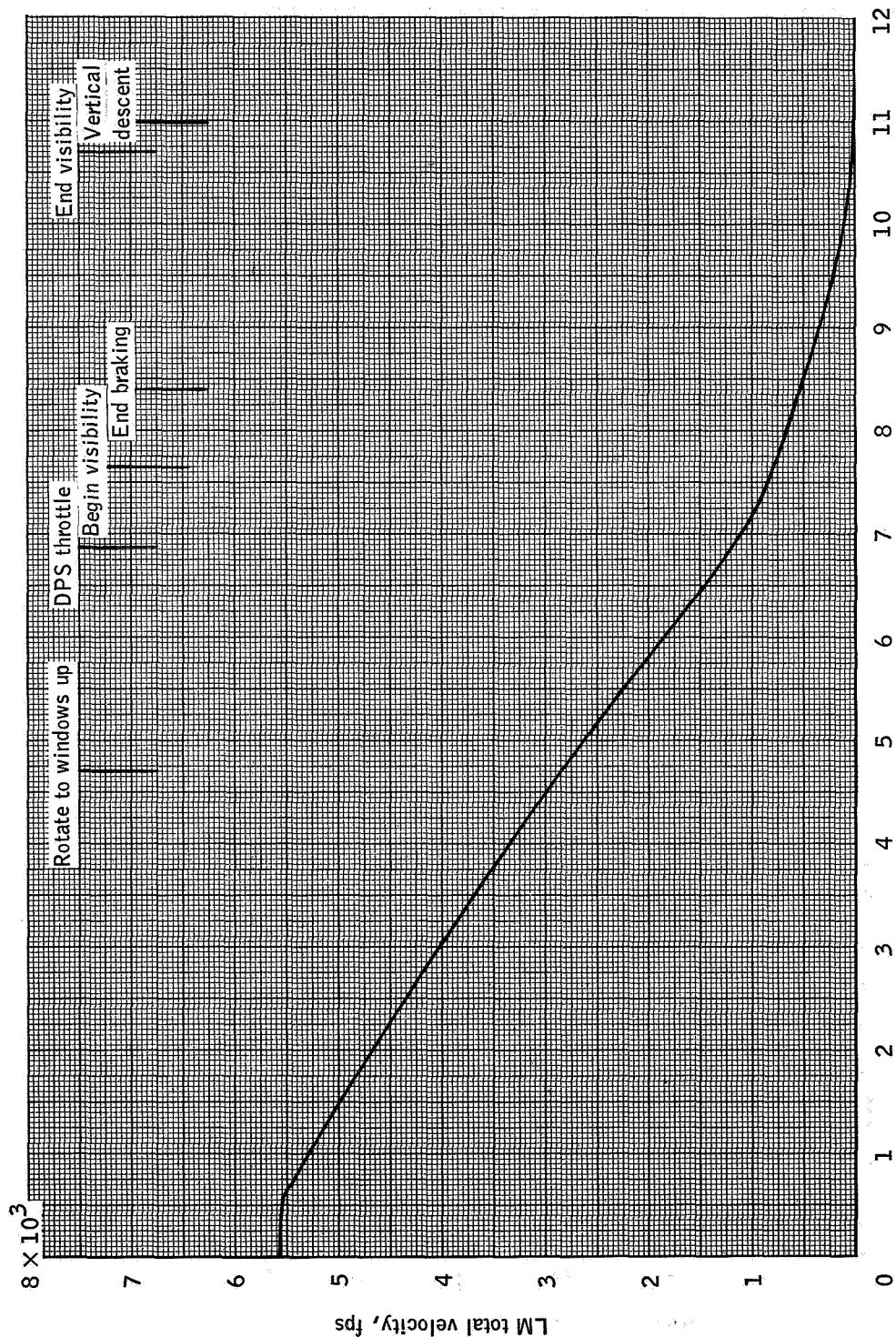
(b) LM-CSM range versus time from powered descent initiation.

Figure 2.- Continued.



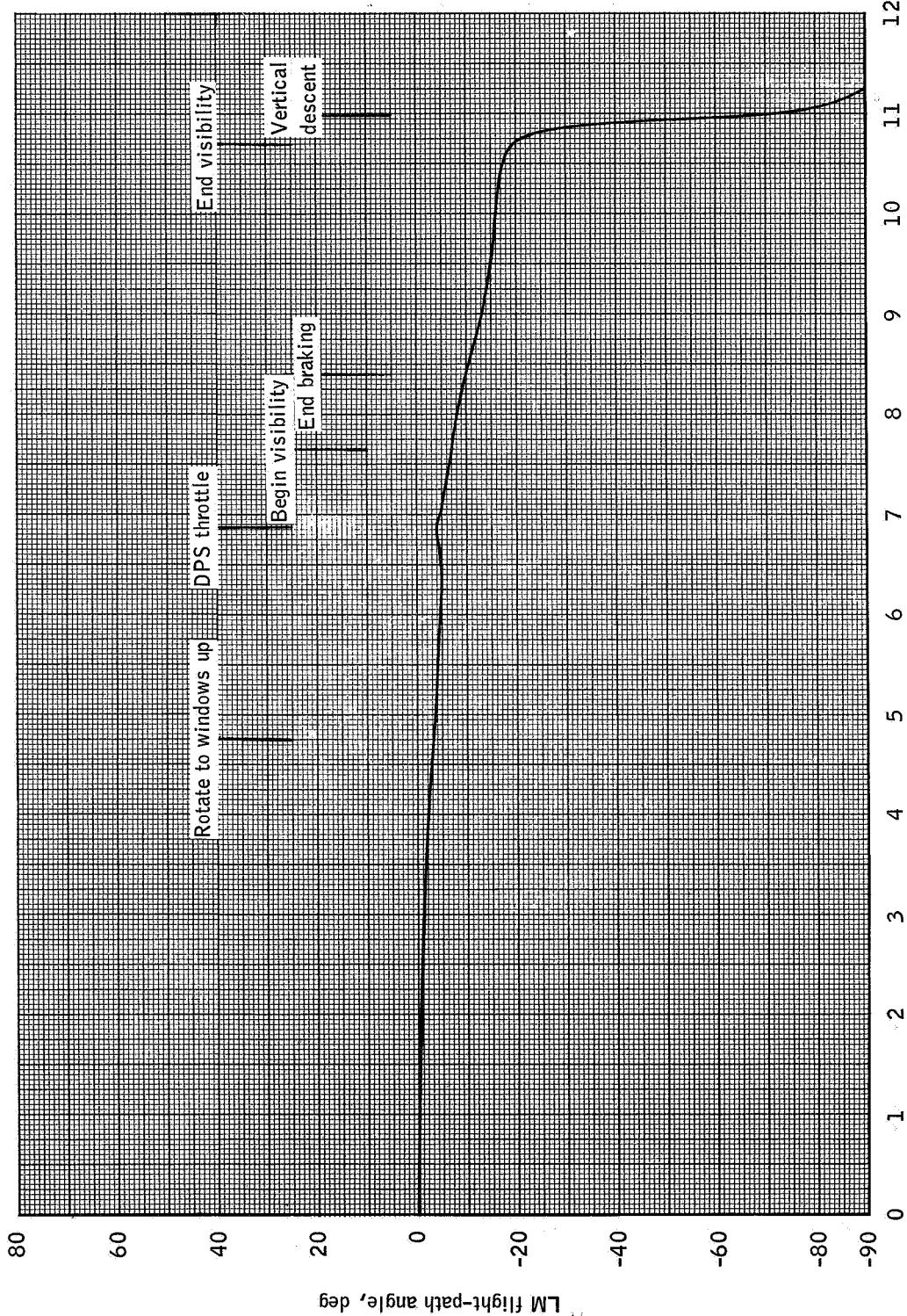
(c) LM-CSM range rate versus time from powered descent initiation.

Figure 2.- Continued.



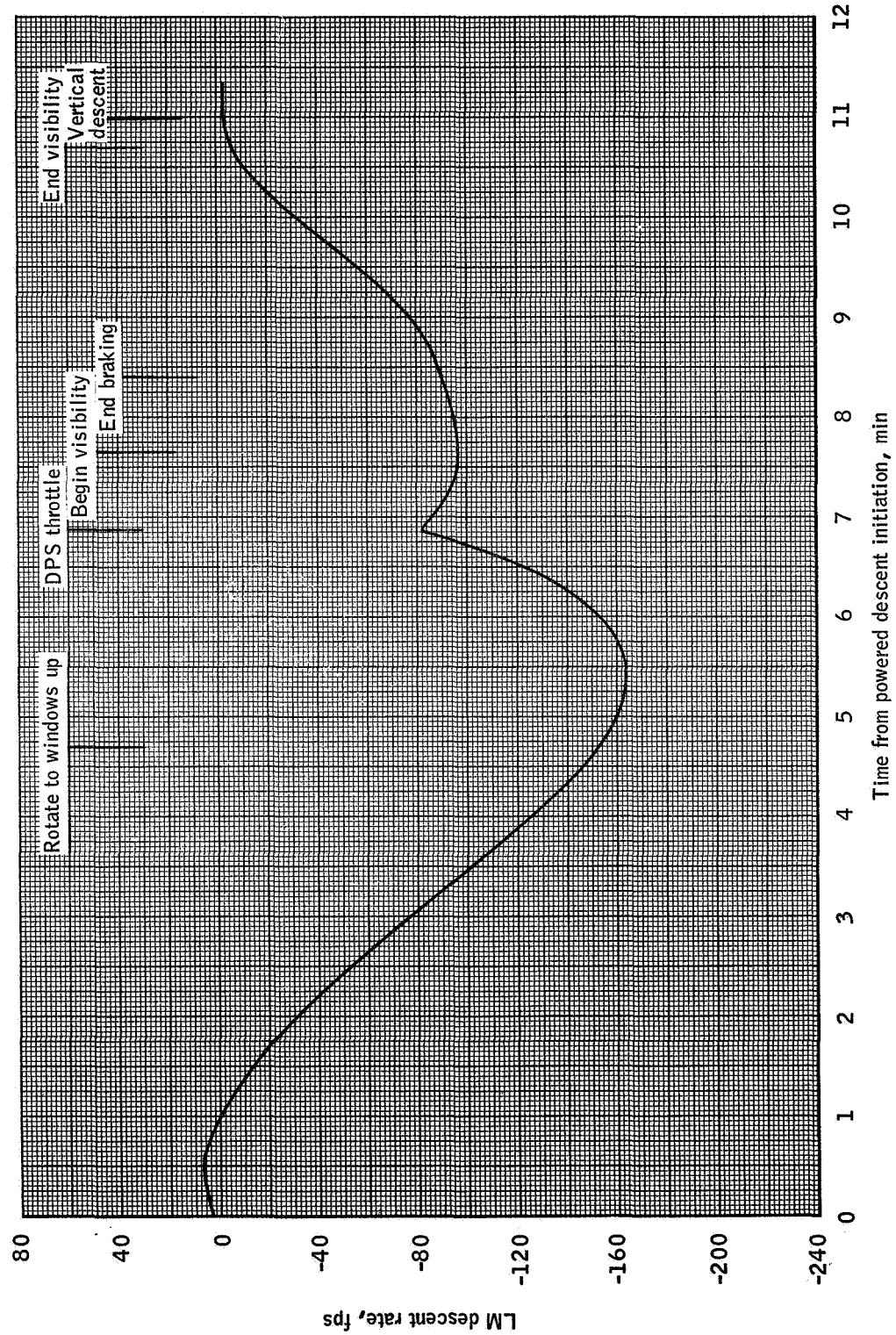
(d) LM total velocity versus time from powered descent initiation.

Figure 2.- Continued.



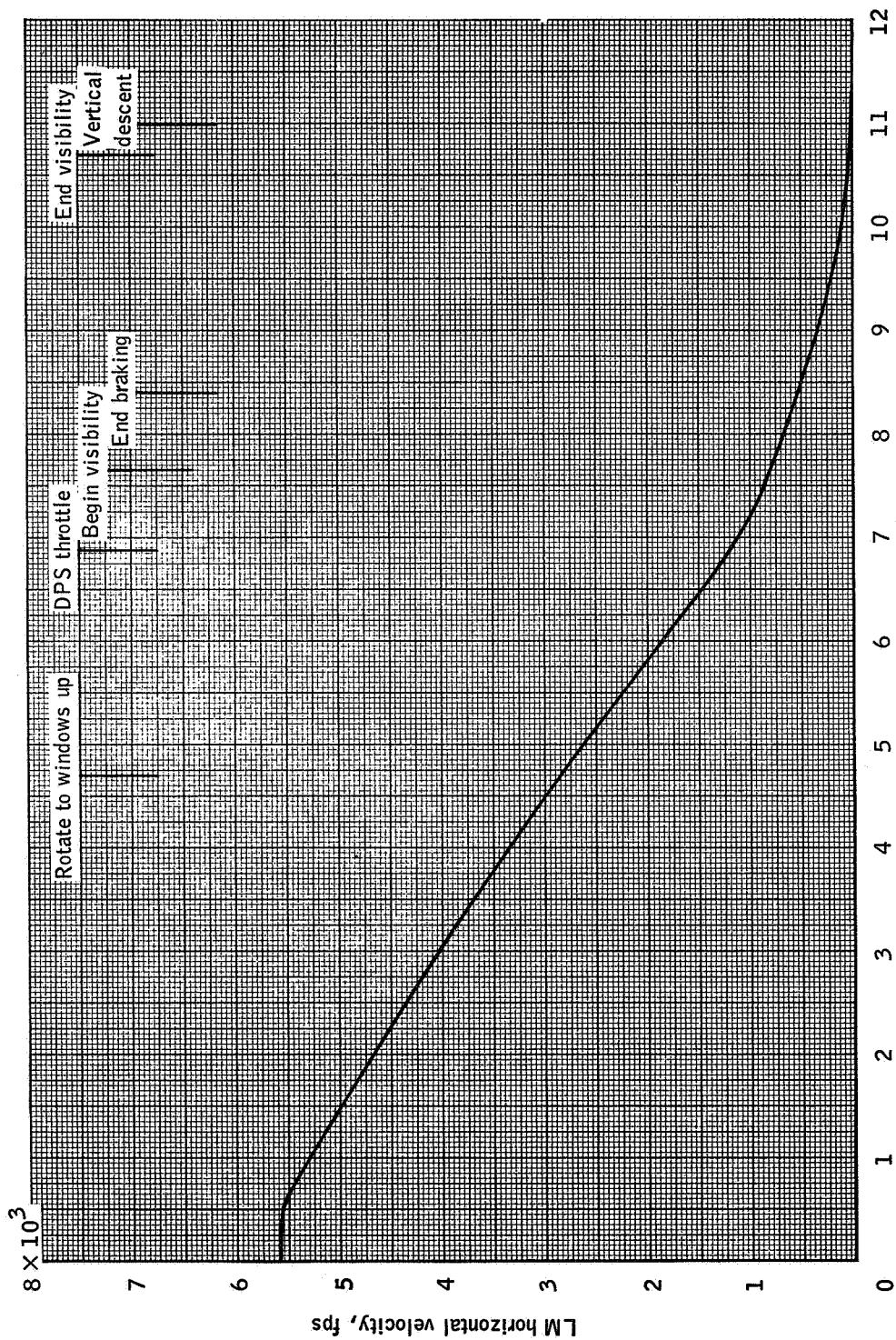
(e) LM flight-path angle versus time from powered descent initiation.

Figure 2 • Continued.



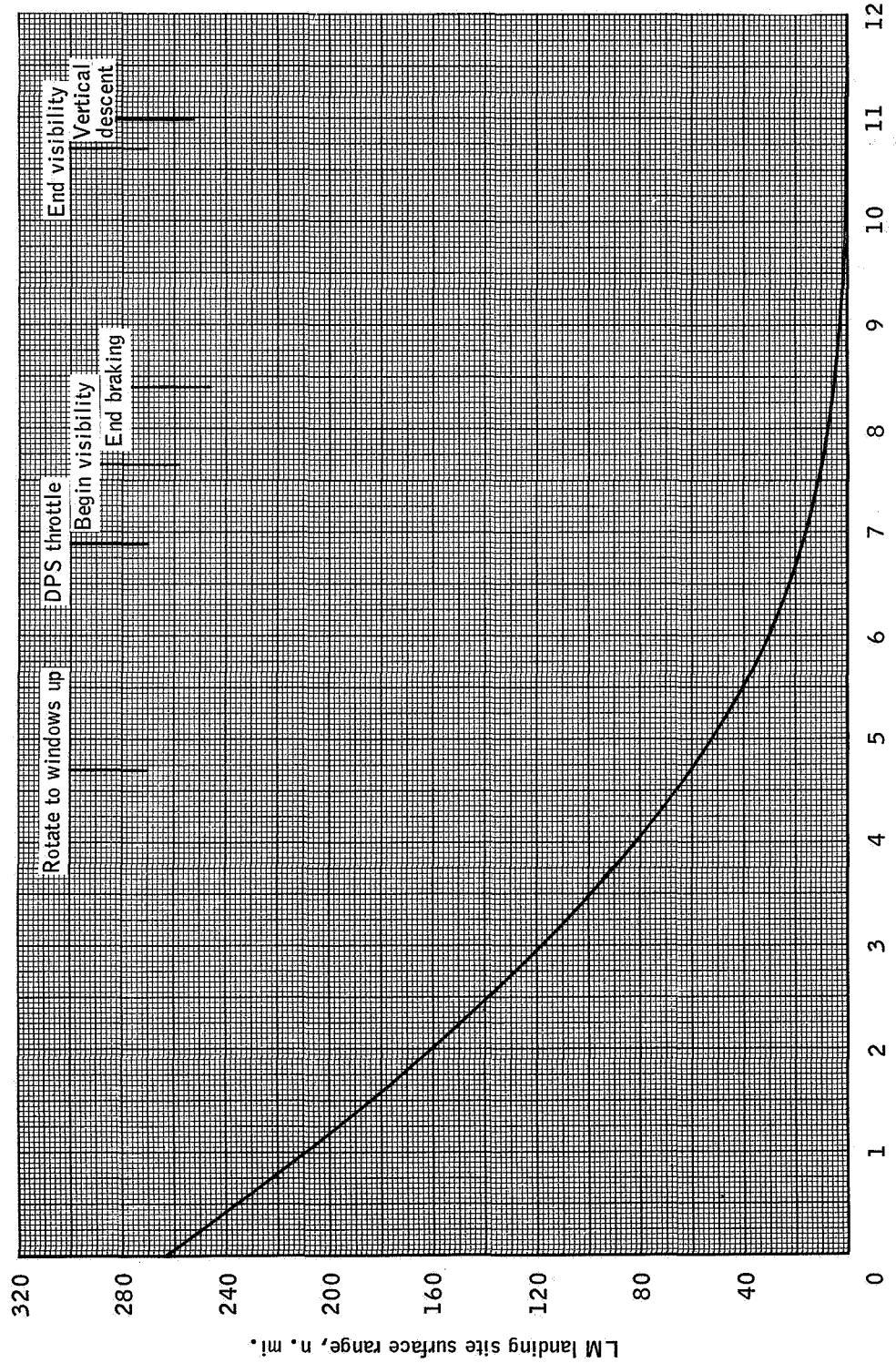
(f) LM descent rate versus time from powered descent initiation.

Figure 2.- Continued.



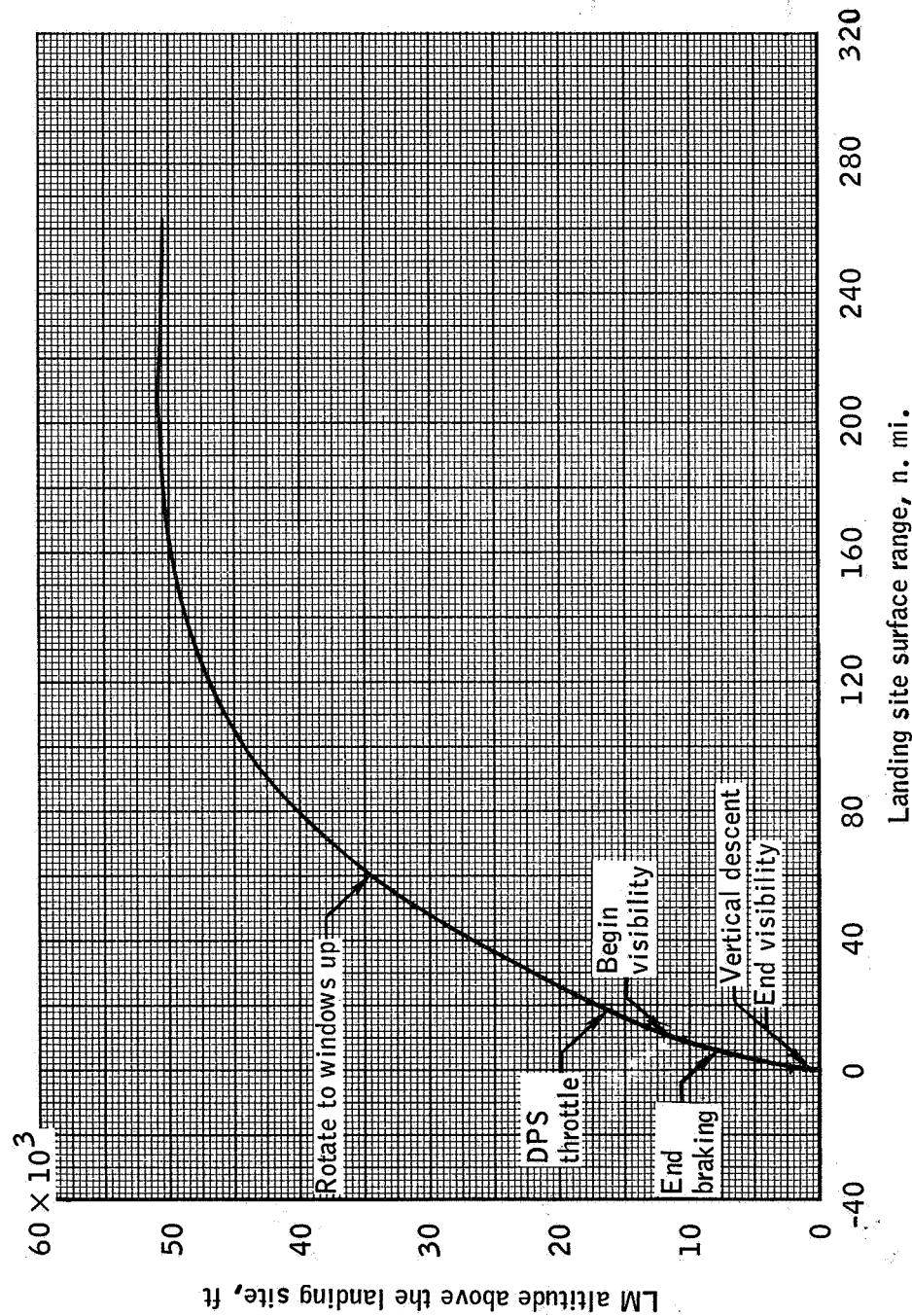
(g) LM horizontal velocity versus time from powered descent initiation.

Figure 2.- Continued.



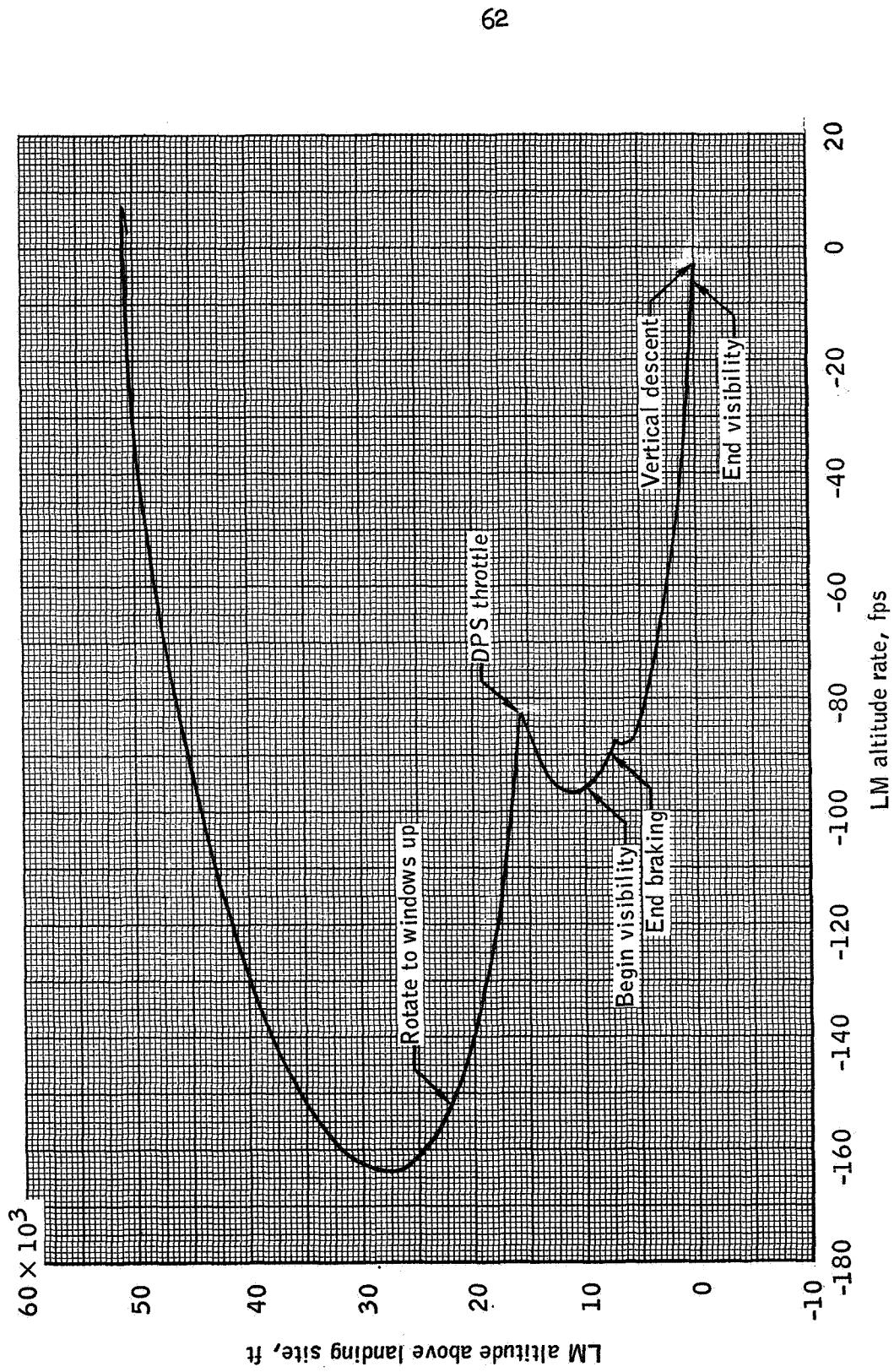
(h) LM landing site surface range versus time from powered descent initiation.

Figure 2.- Continued.



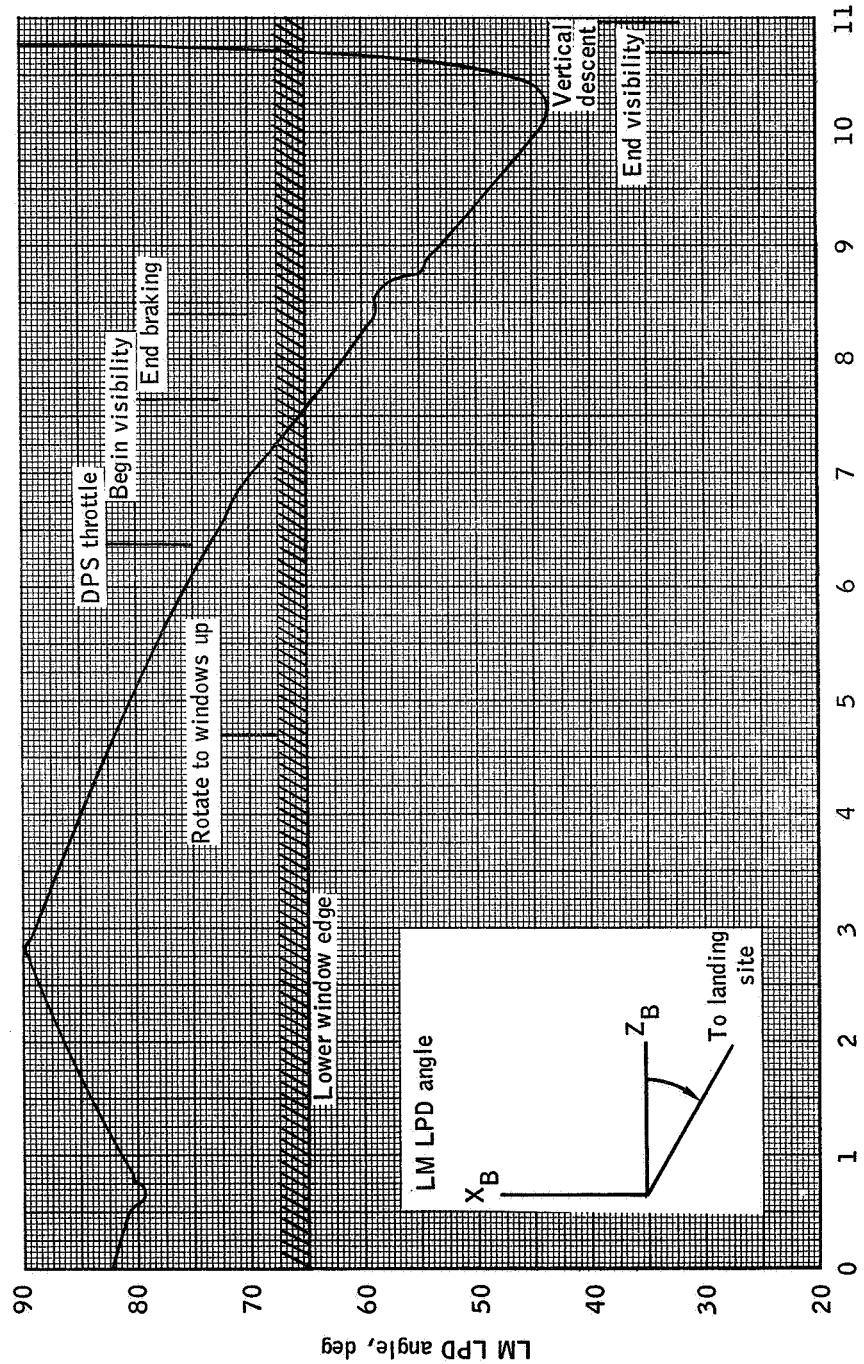
(i) LM altitude above the landing site versus the landing site surface range.

Figure 2.- Continued.



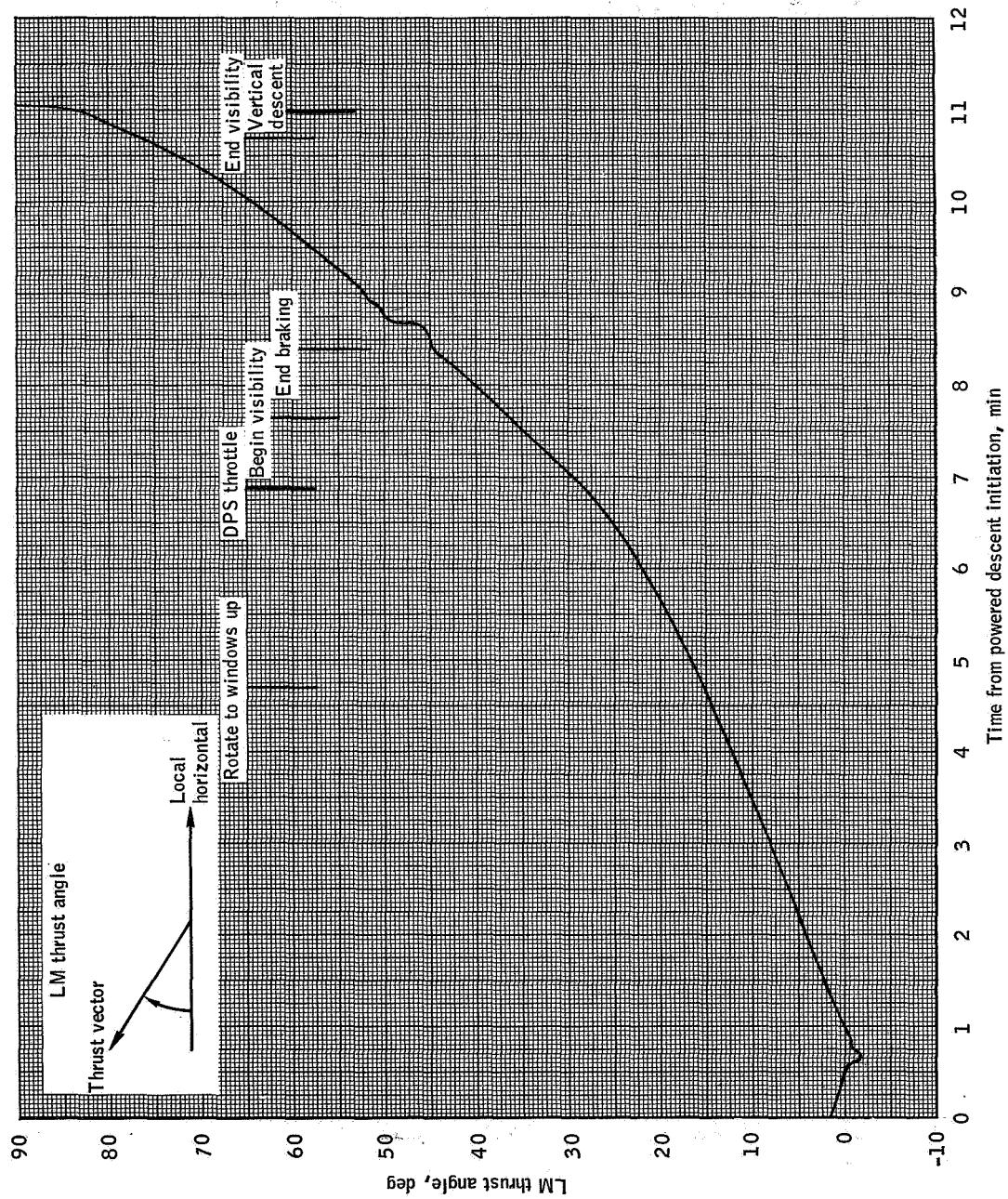
(j) LM altitude above landing site versus altitude rate.

Figure 2.- Continued.



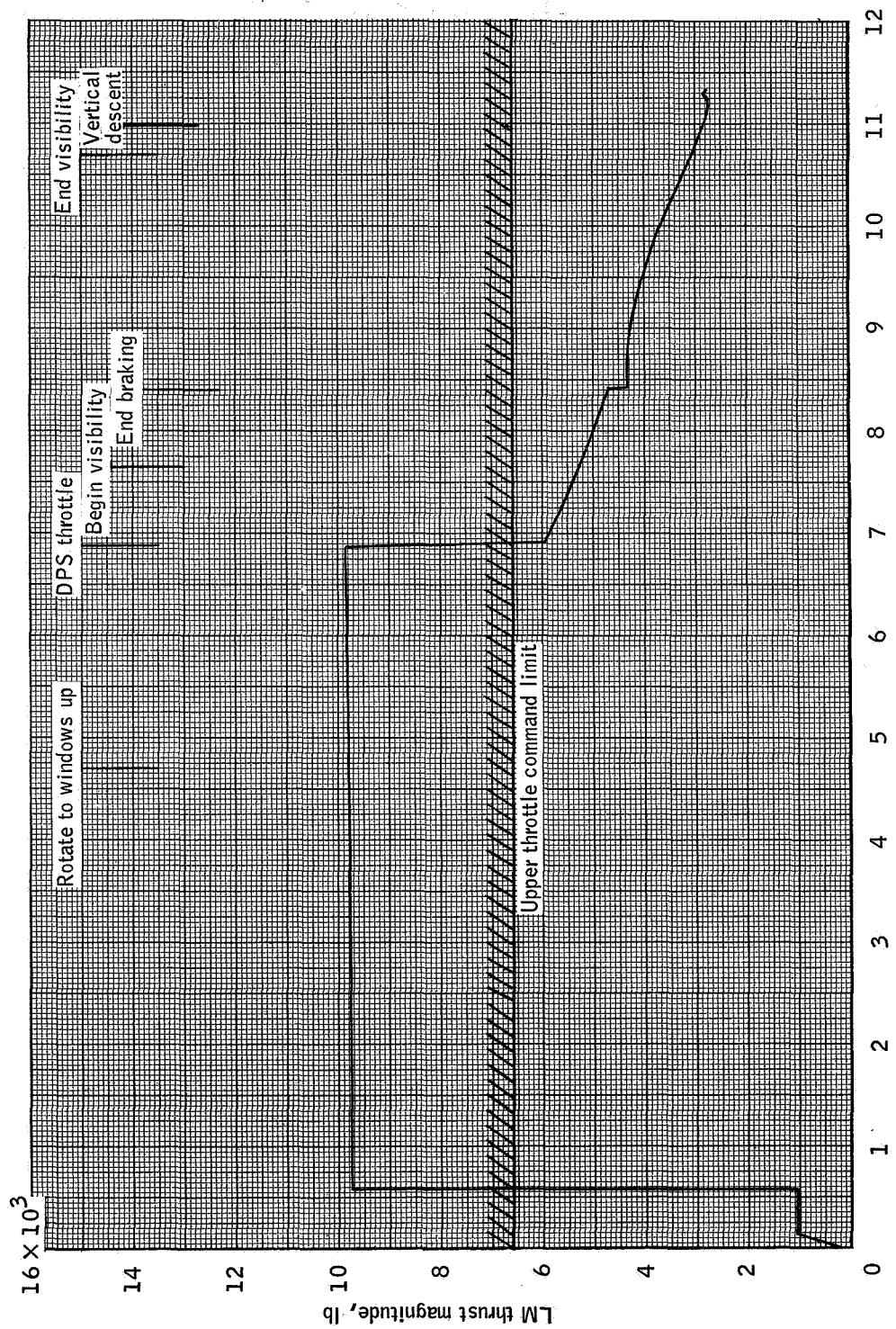
(k) LM LPD angle versus time from powered descent initiation.

Figure 2.- Continued.



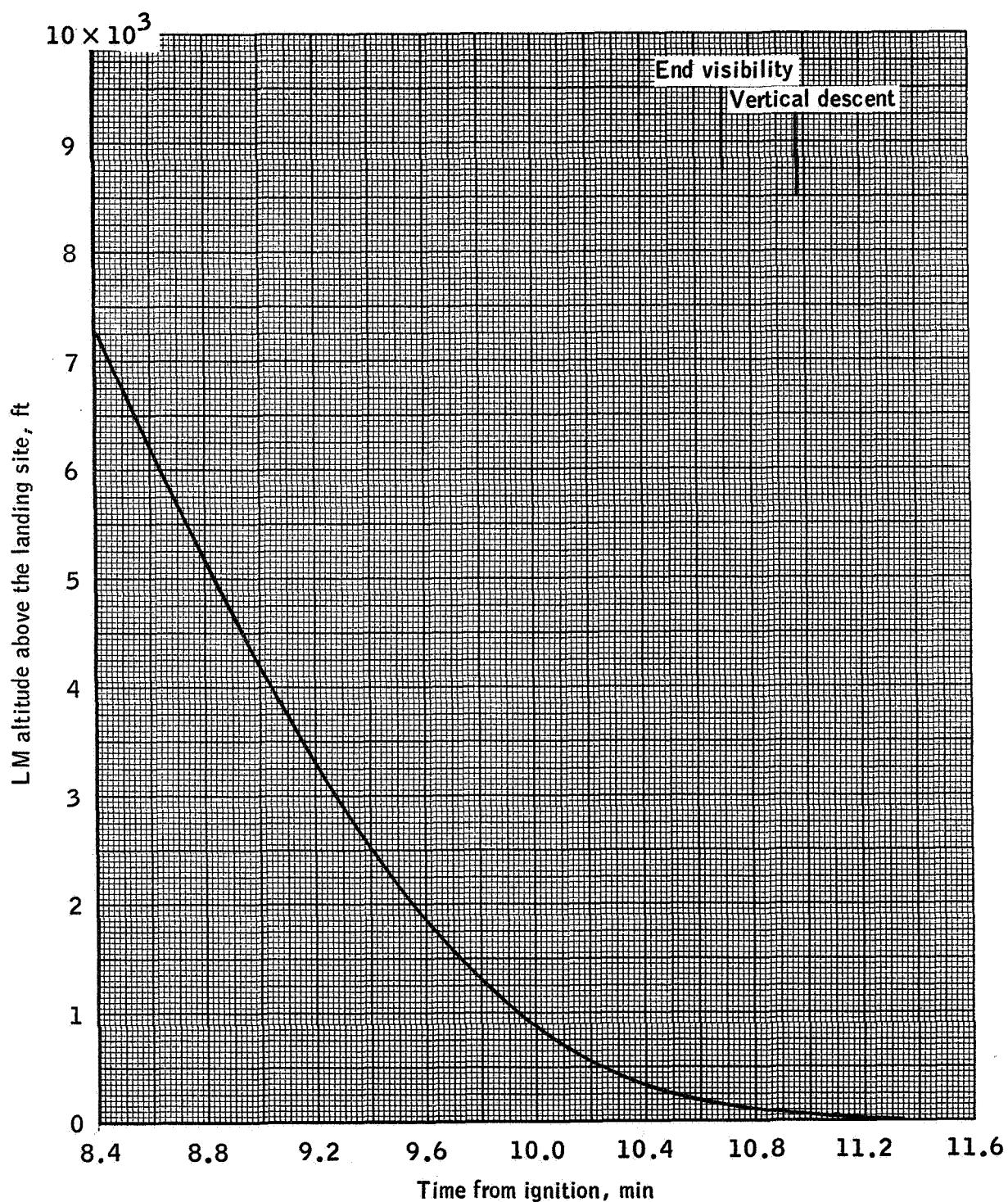
(1) LM thrust angle versus time from powered descent initiation.

Figure 2.-r Continued.



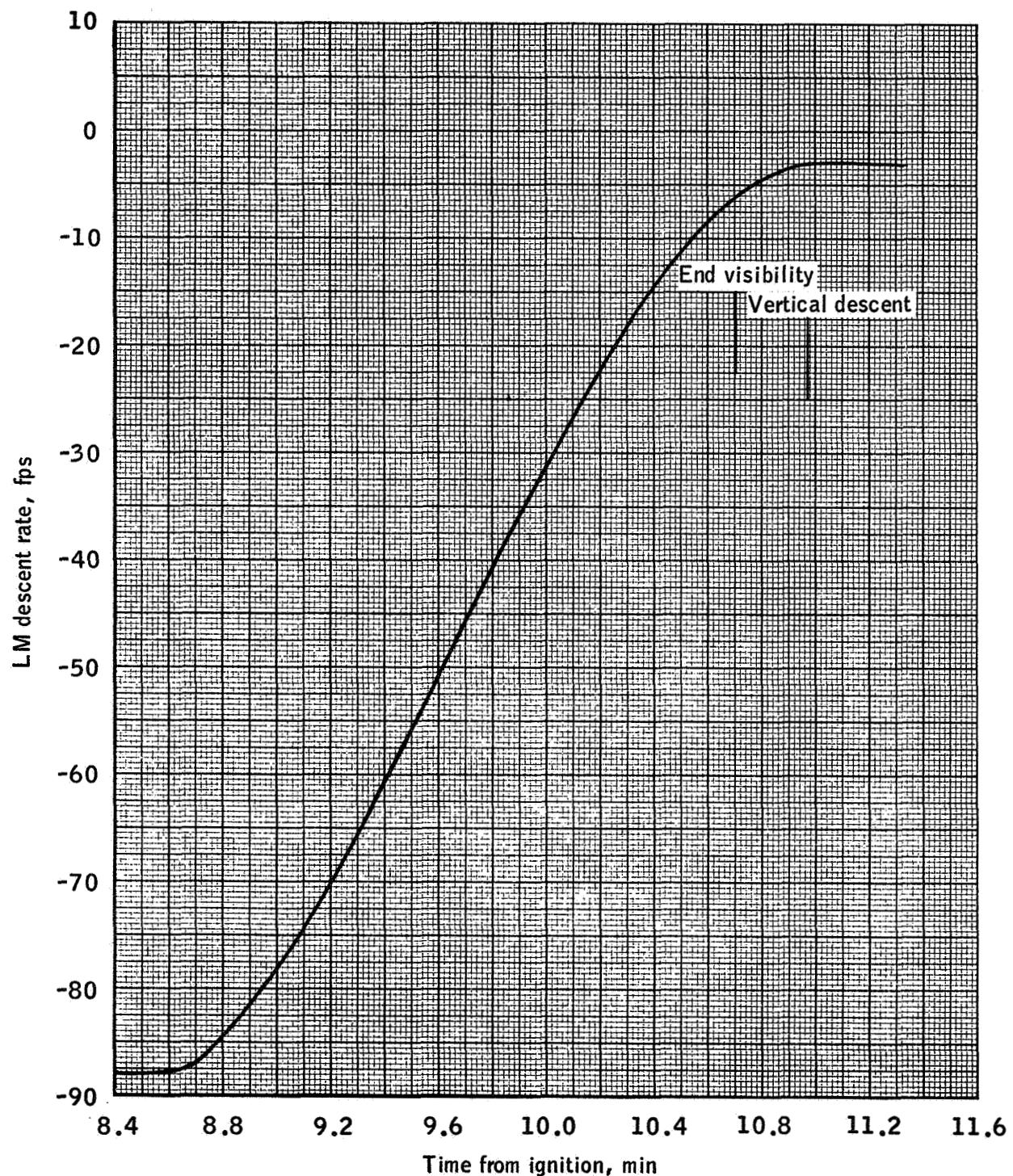
(m) LM thrust magnitude versus time from powered descent initiation.

Figure 2.- Concluded.



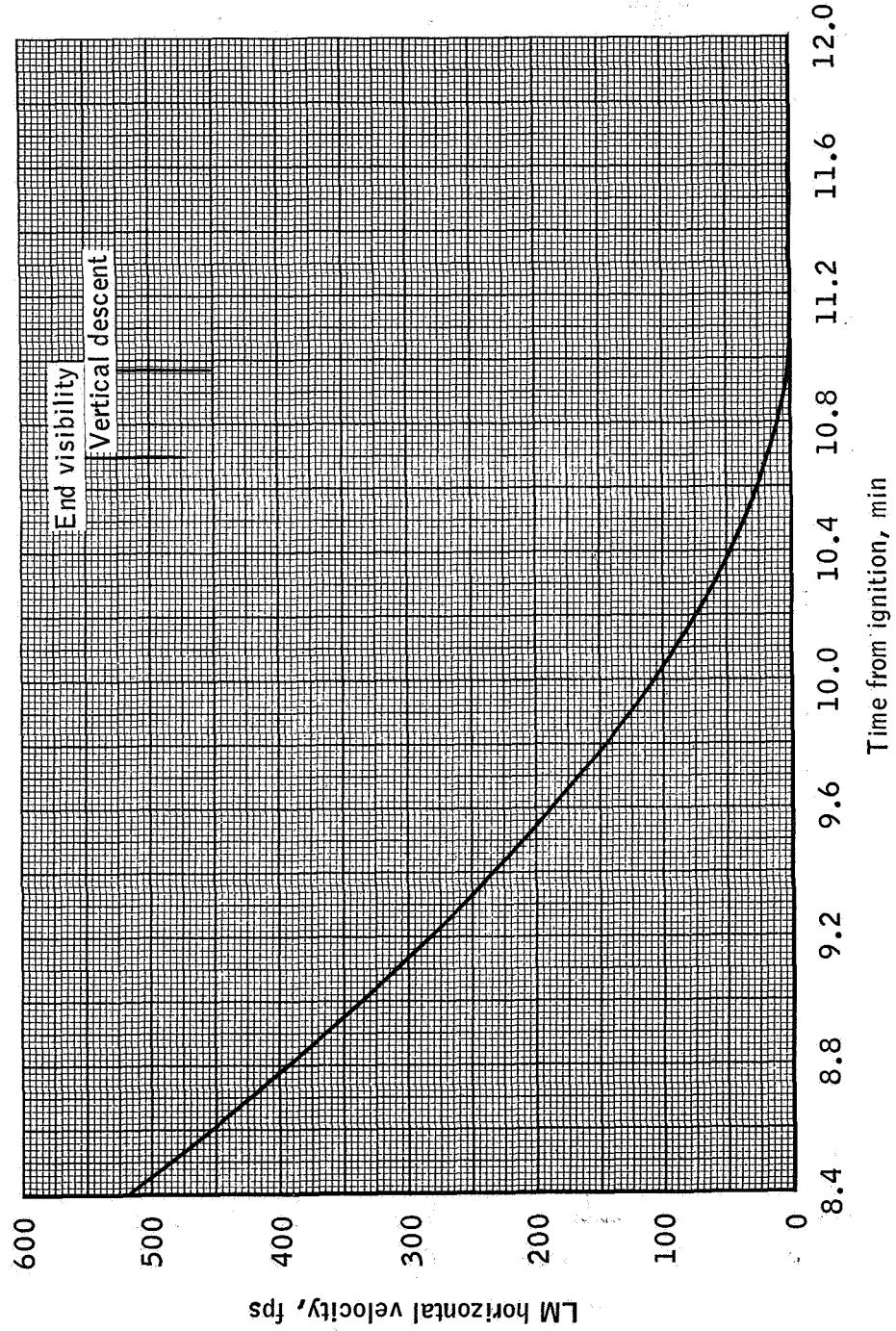
(a) LM altitude above the landing site versus time from ignition.

Figure 3.- Lunar module descent - approach and landing.



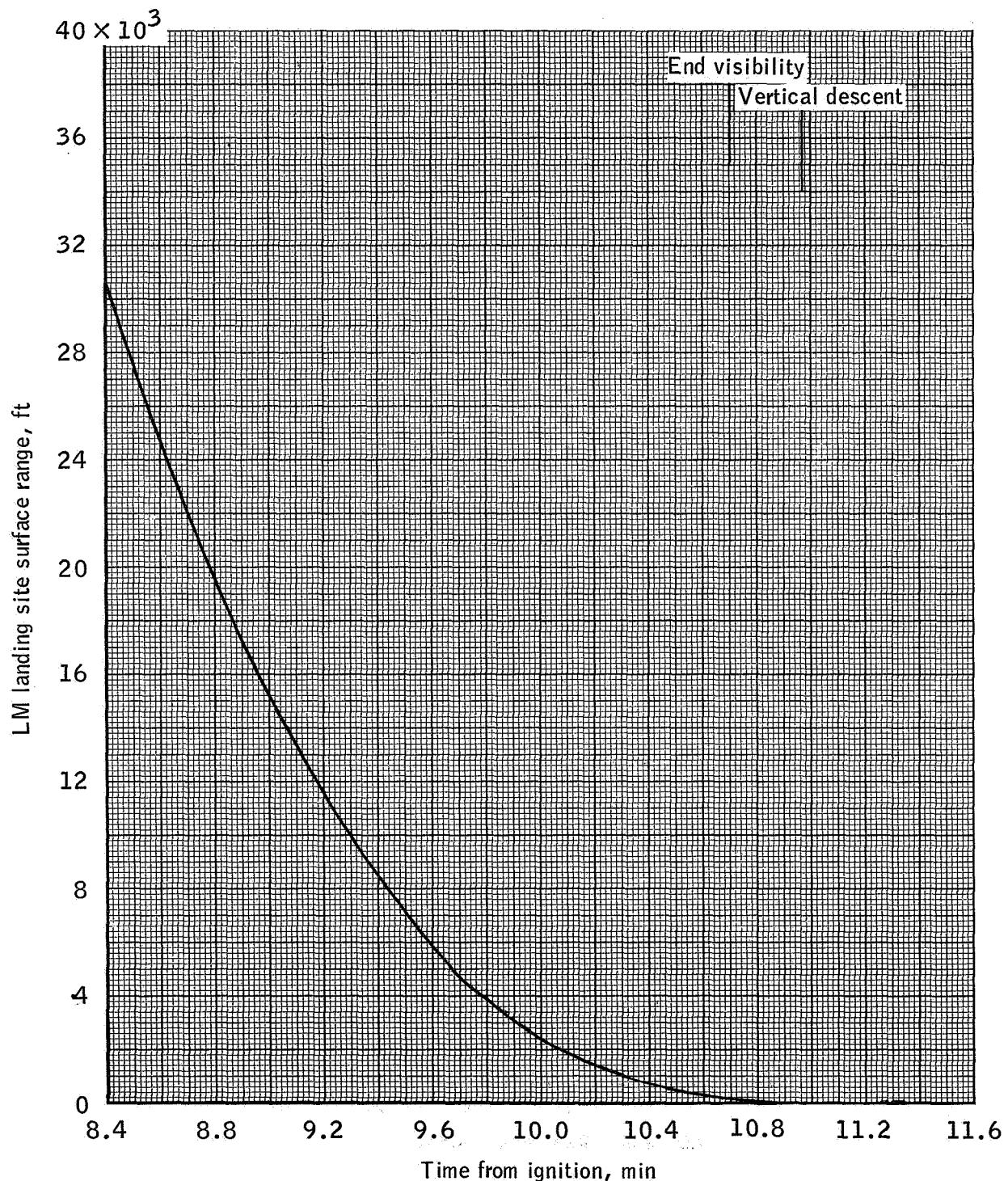
(b) LM descent rate versus time from ignition.

Figure 3.- Continued.



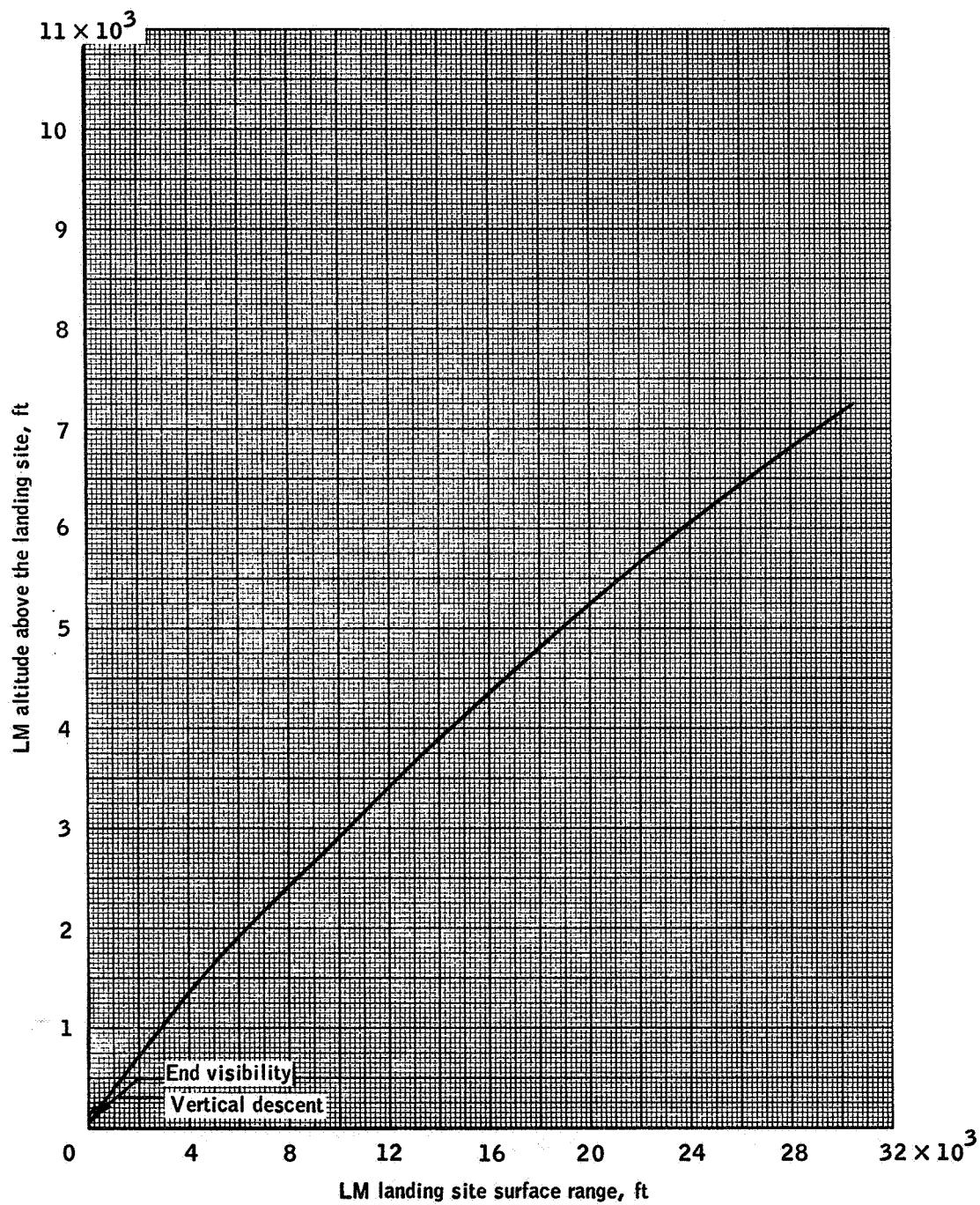
(c) LM horizontal velocity versus time from ignition.

Figure 3.- Continued.



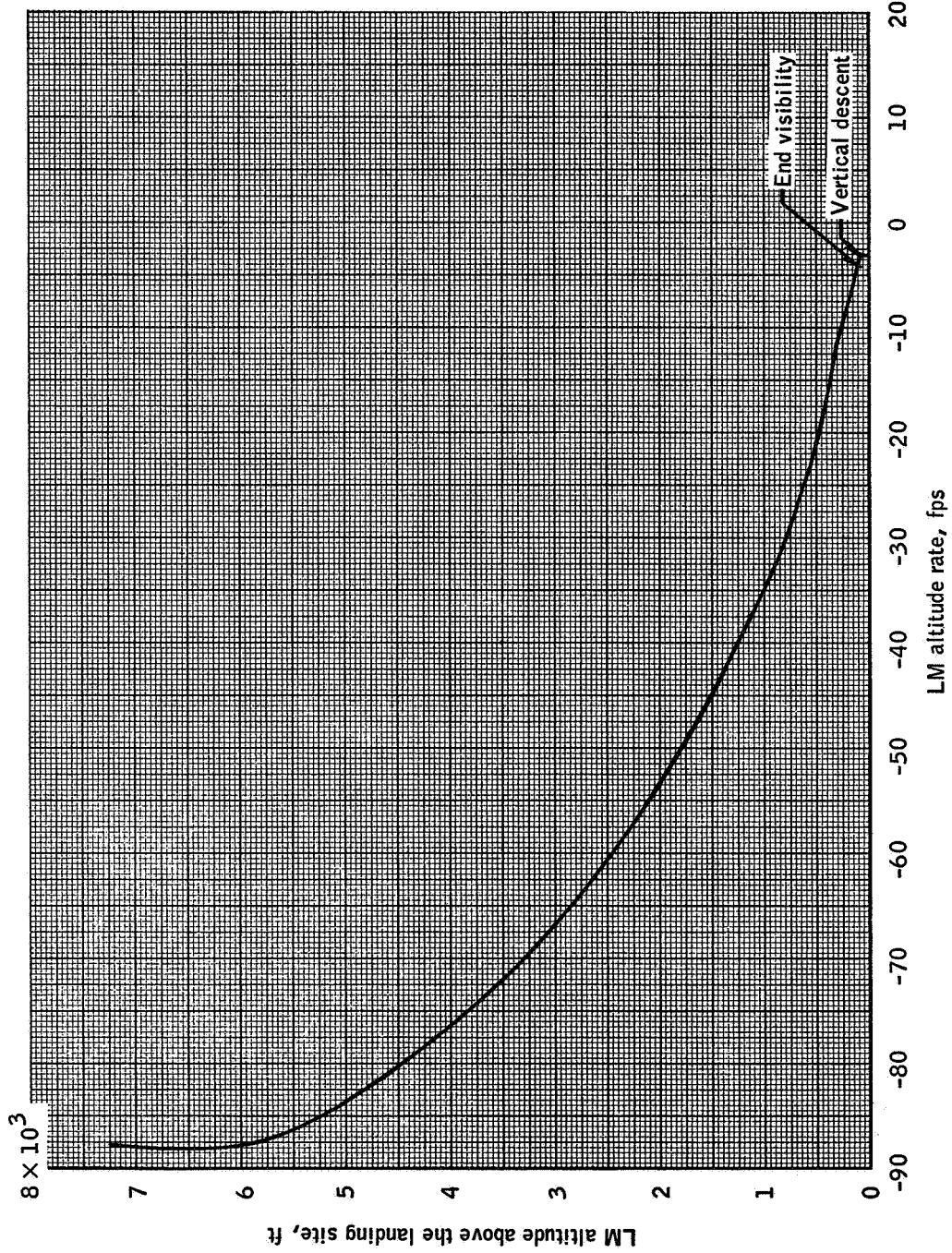
(d) LM landing site surface range versus time from ignition.

Figure 3.- Continued.



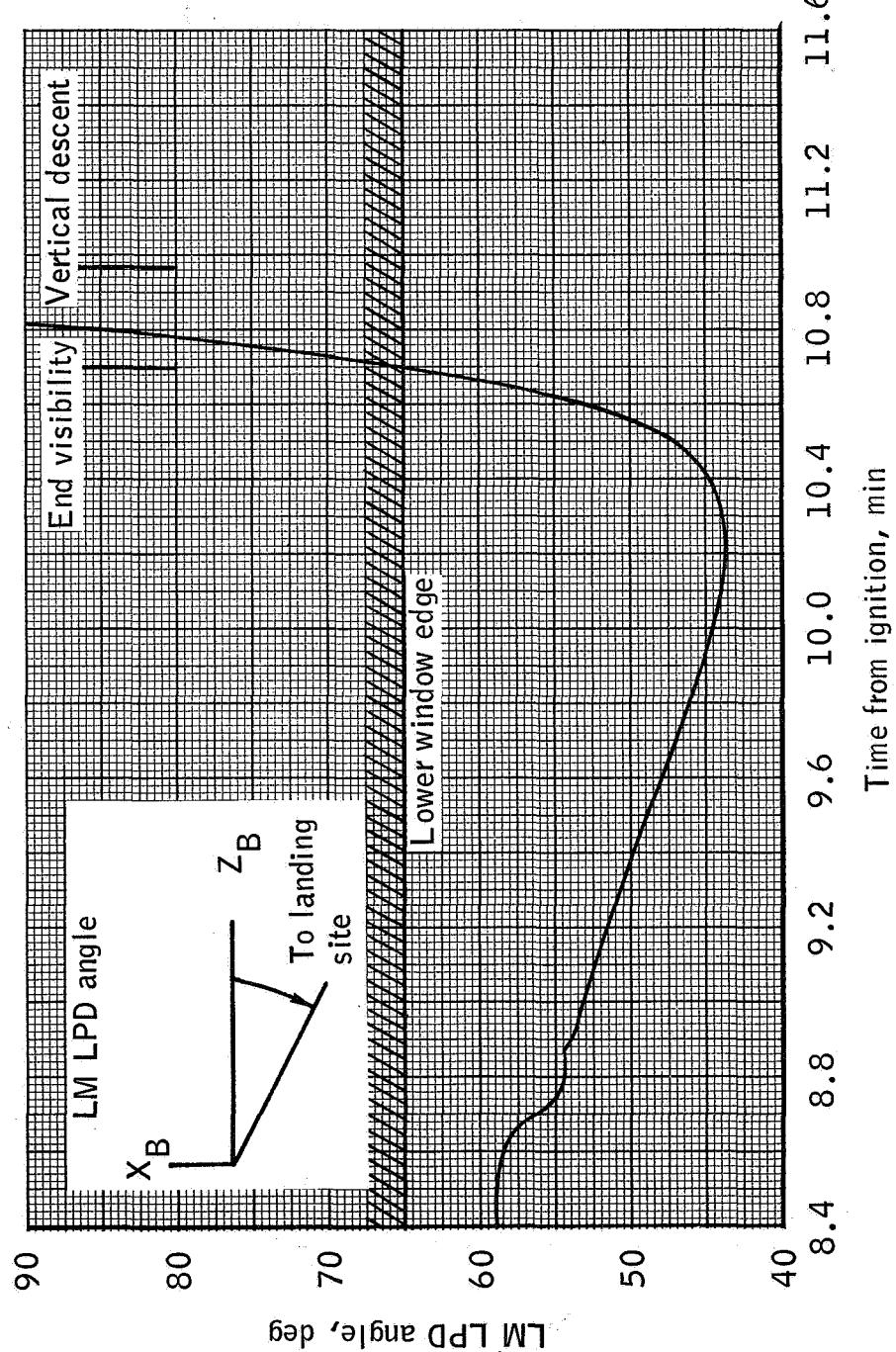
(e) LM altitude above the landing site versus landing site surface range.

Figure 3.- Continued.



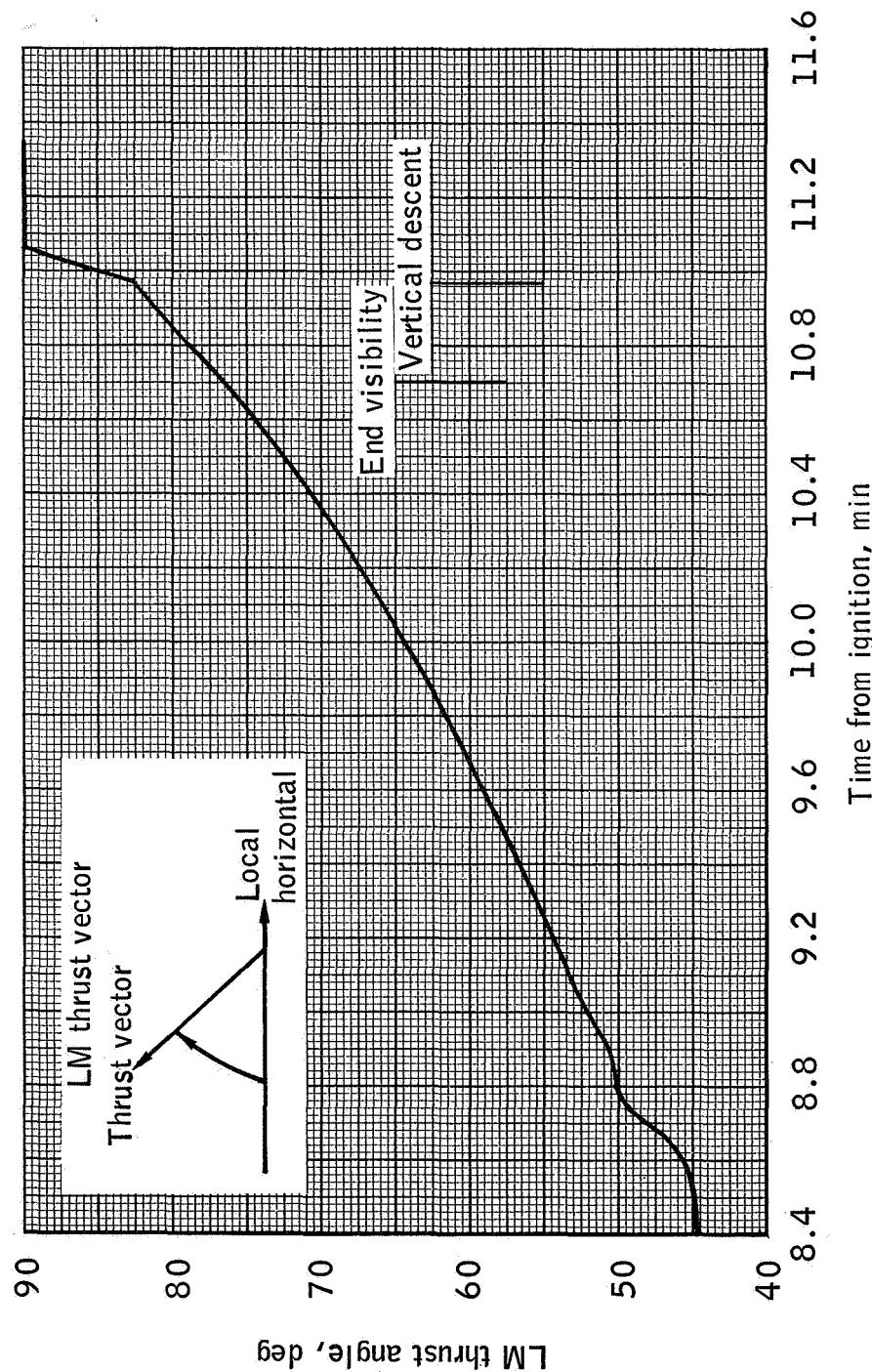
(f) LM altitude above the landing site versus altitude rate.

Figure 3.- Continued.



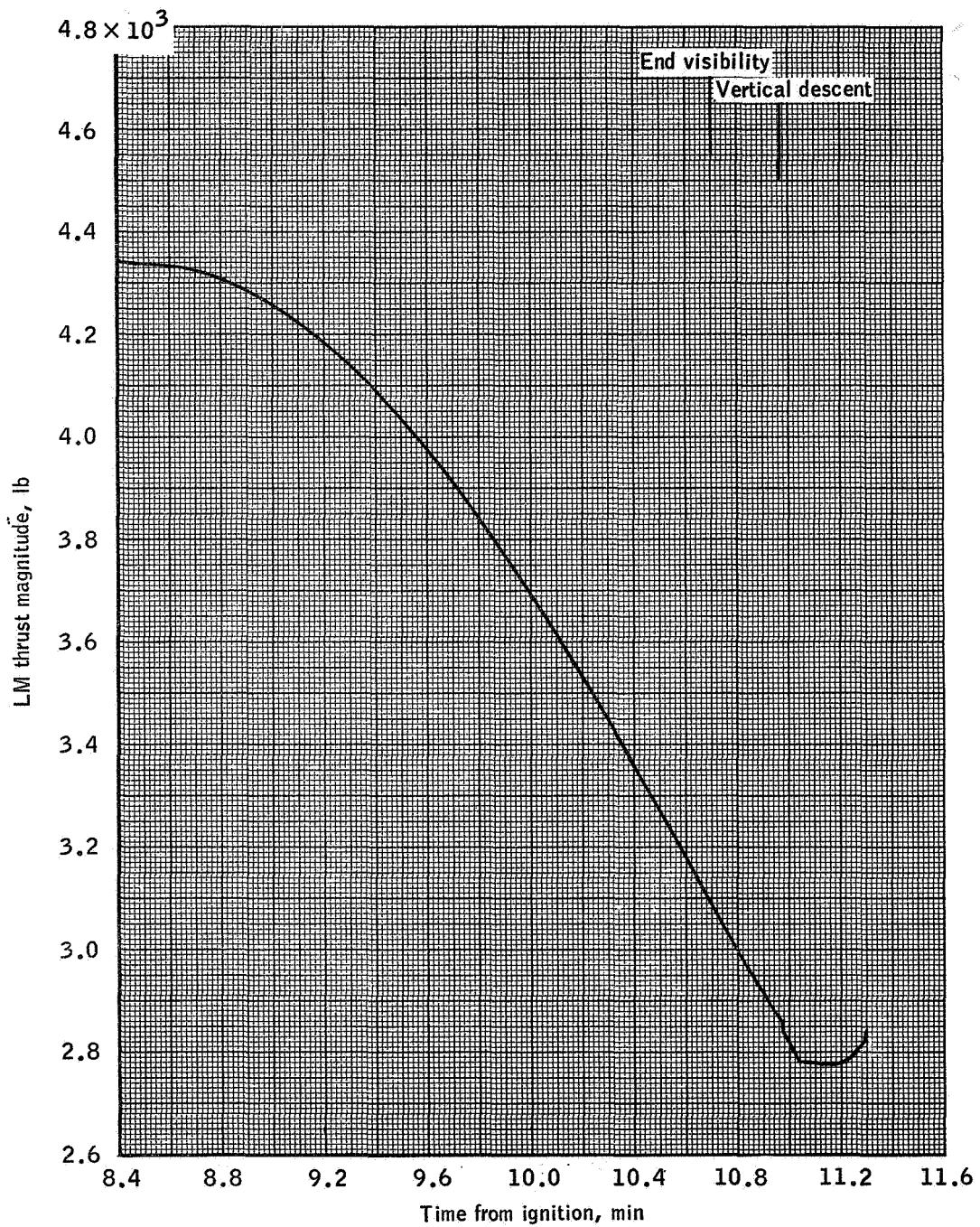
(g) LM LPD angle versus time from ignition.

Figure 3.- Continued.



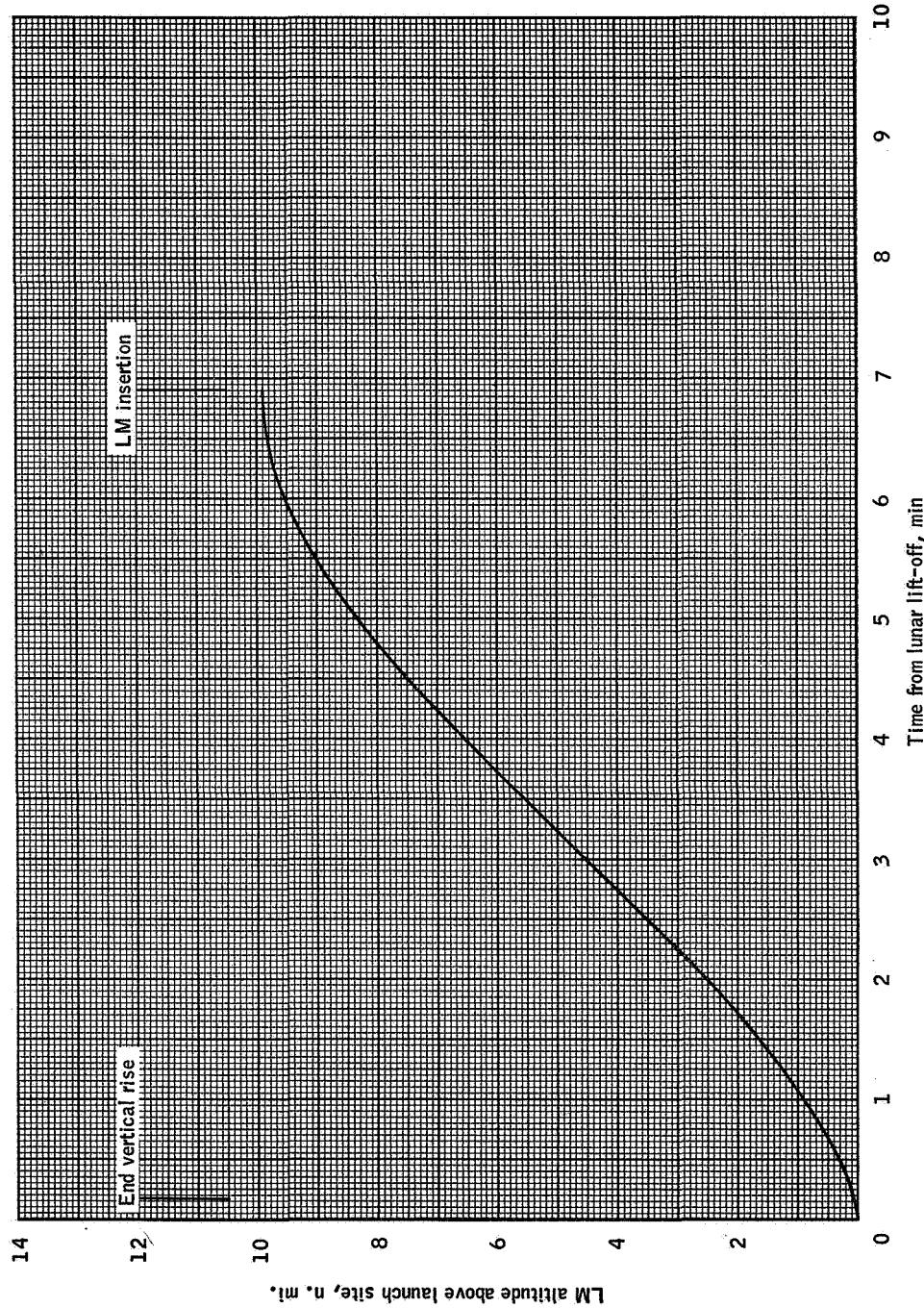
(h) LM thrust angle versus time from ignition.

Figure 3 .-- Continued.



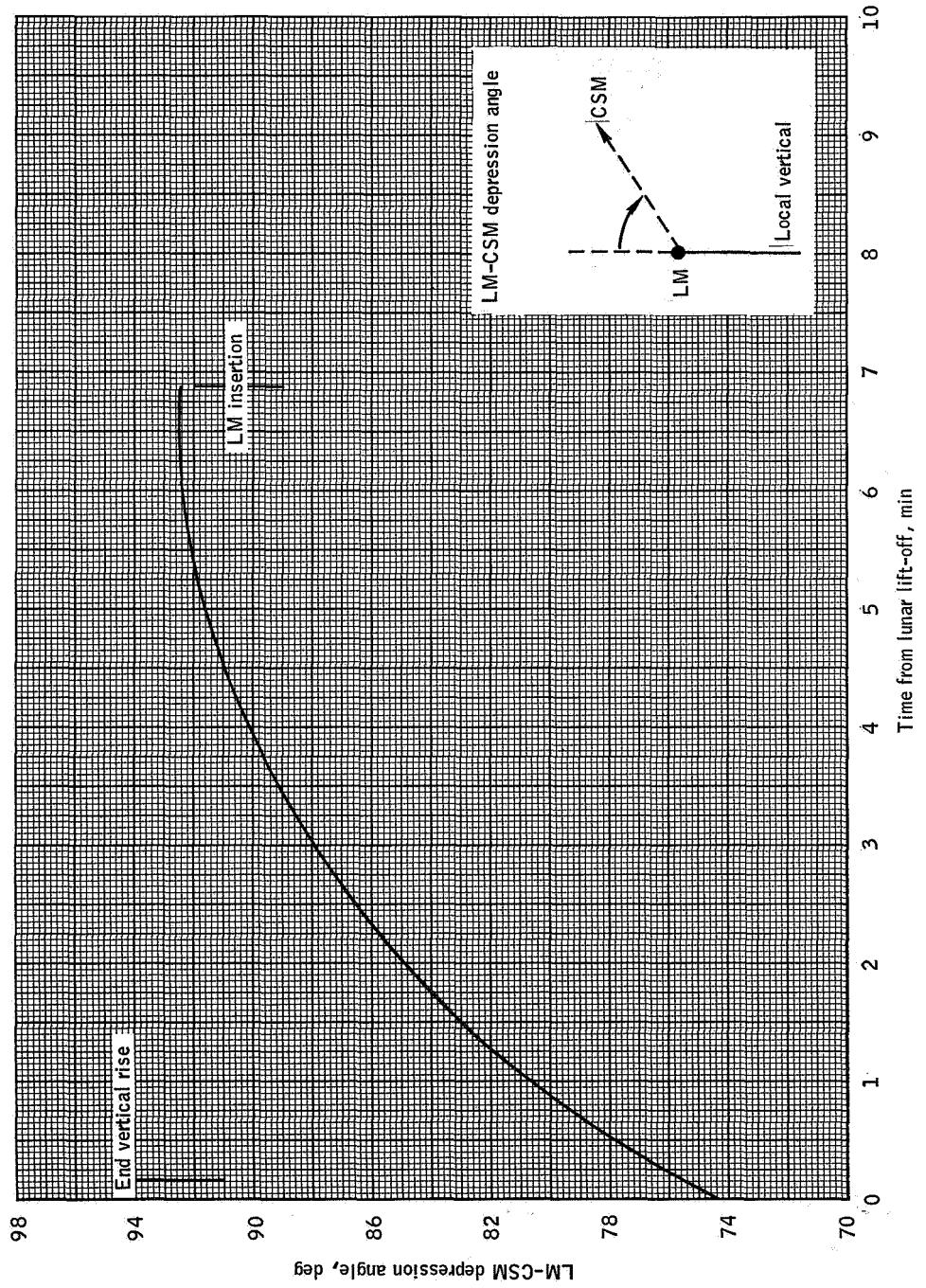
(i) LM thrust magnitude versus time from ignition.

Figure 3.- Concluded.



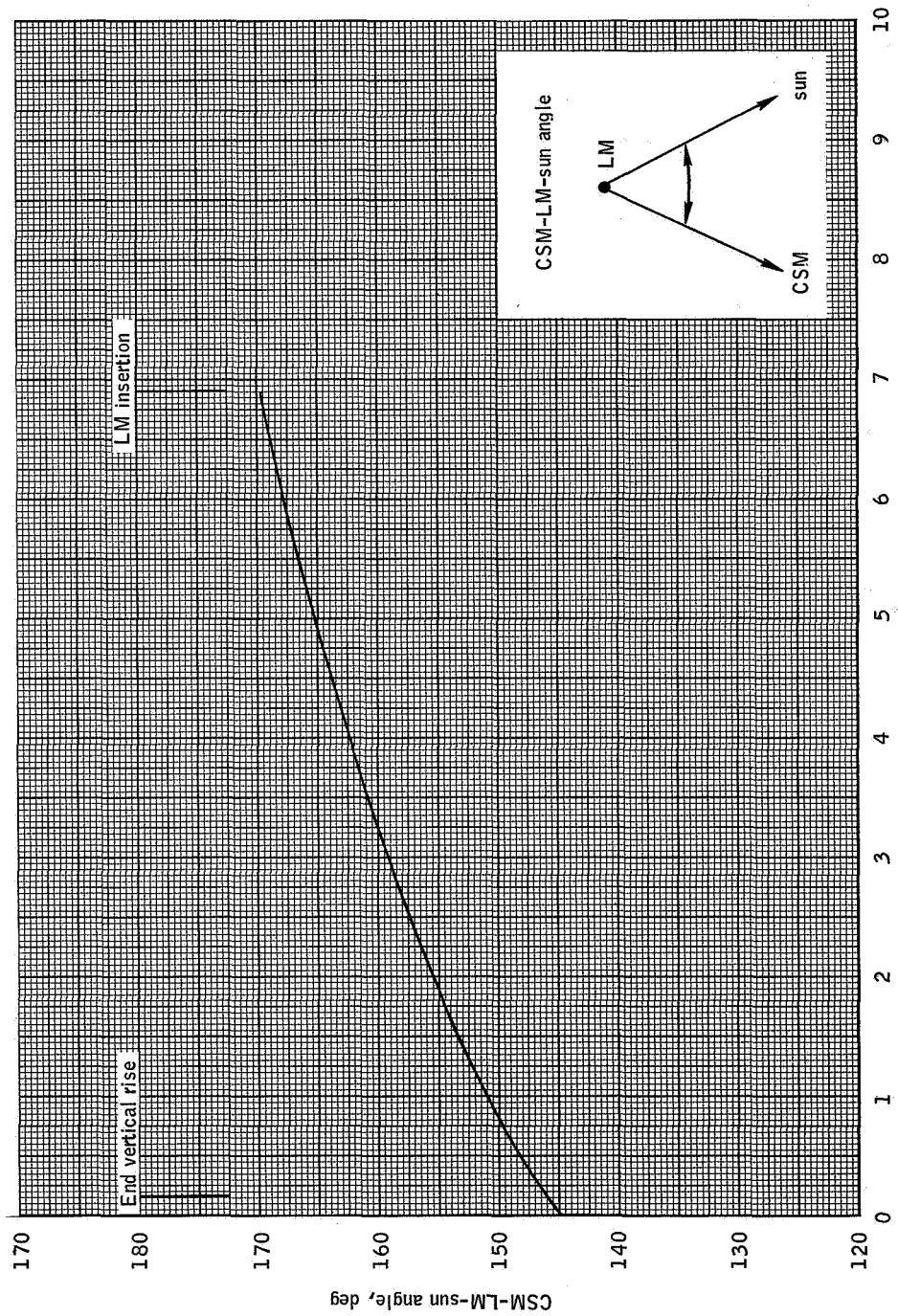
(a) LM altitude above launch site versus time from lunar lift-off.

Figure 4. - Lunar module powered ascent.



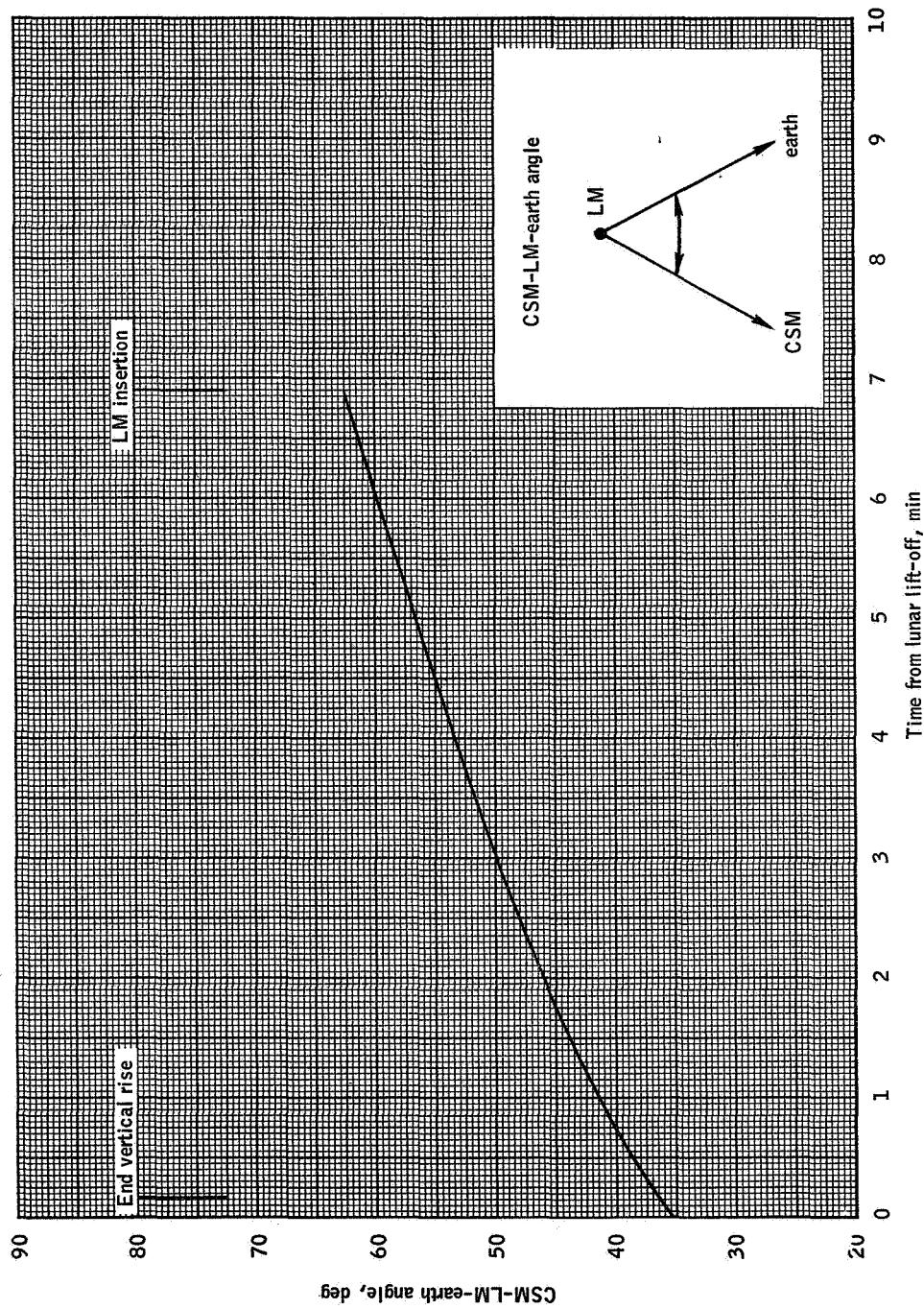
(b) LM-CSM depression angle versus time from lunar lift-off.

Figure 4.- Continued.



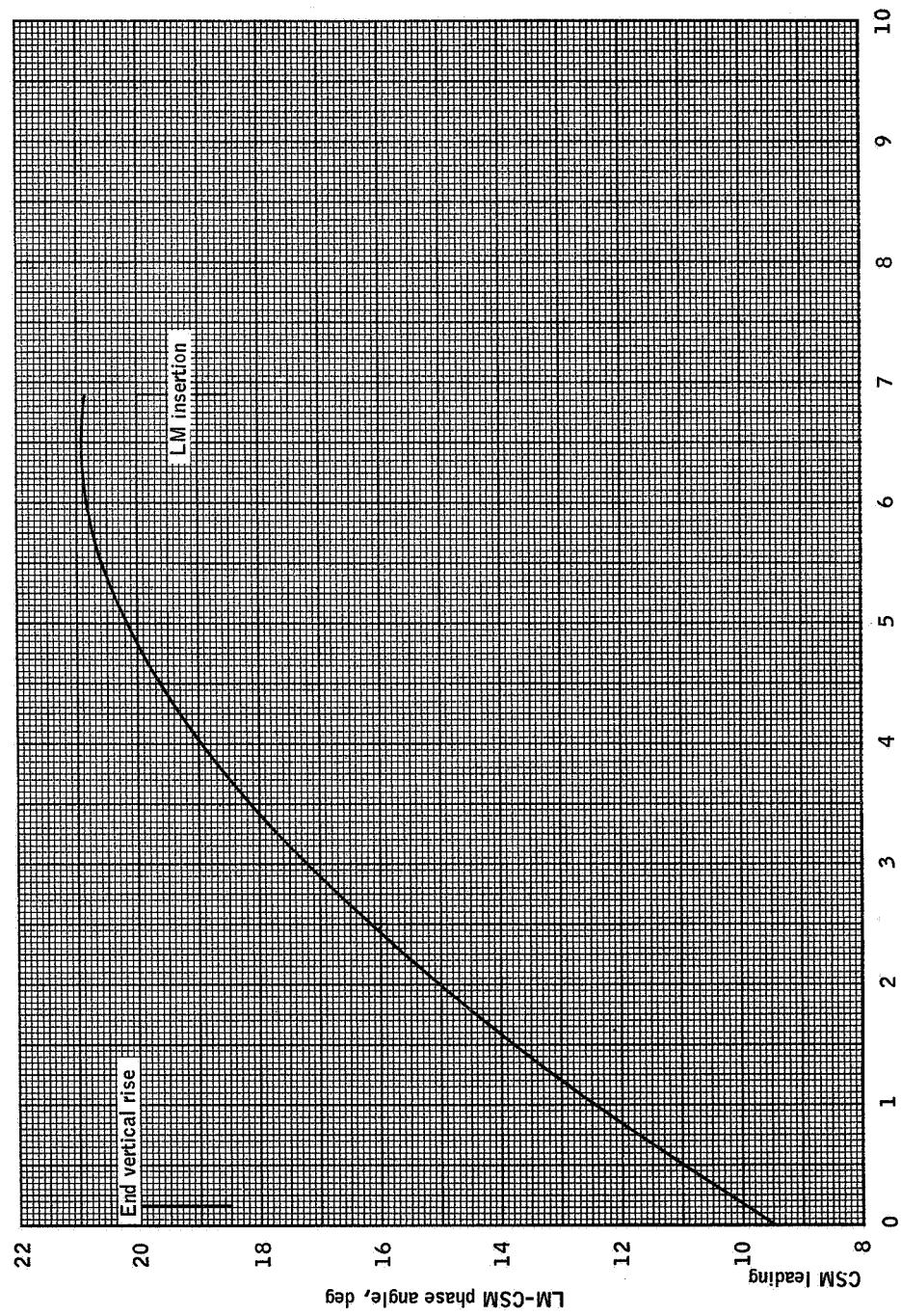
(c) CSM-LM-sun angle versus time from lunar lift-off.

Figure 4. - Continued.



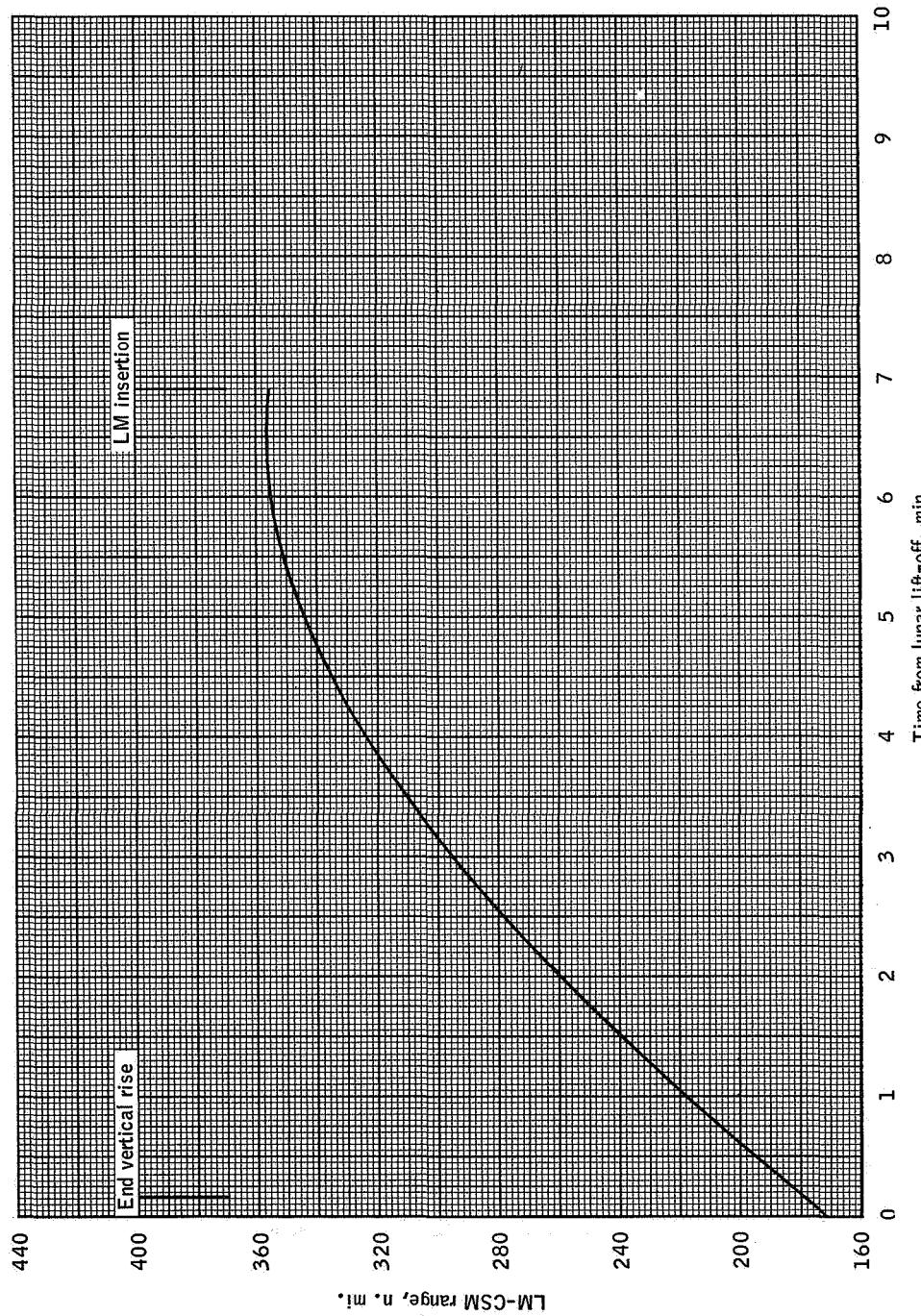
(d) CSM-LM-earth angle versus time from lunar lift-off.

Figure 4.- Continued.



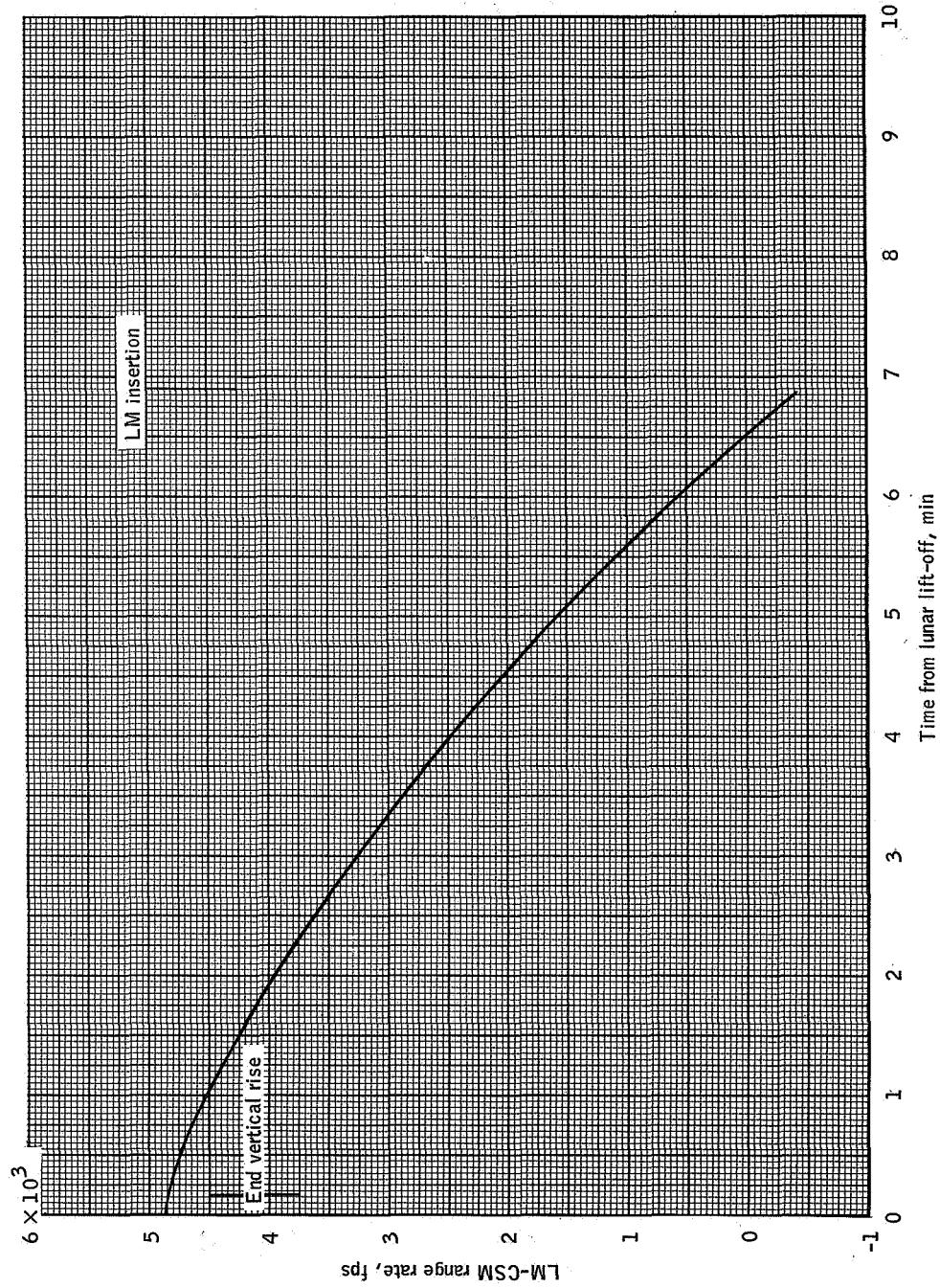
(e) LM-CSM phase angle versus time from lunar lift-off.

Figure 4.- Continued.



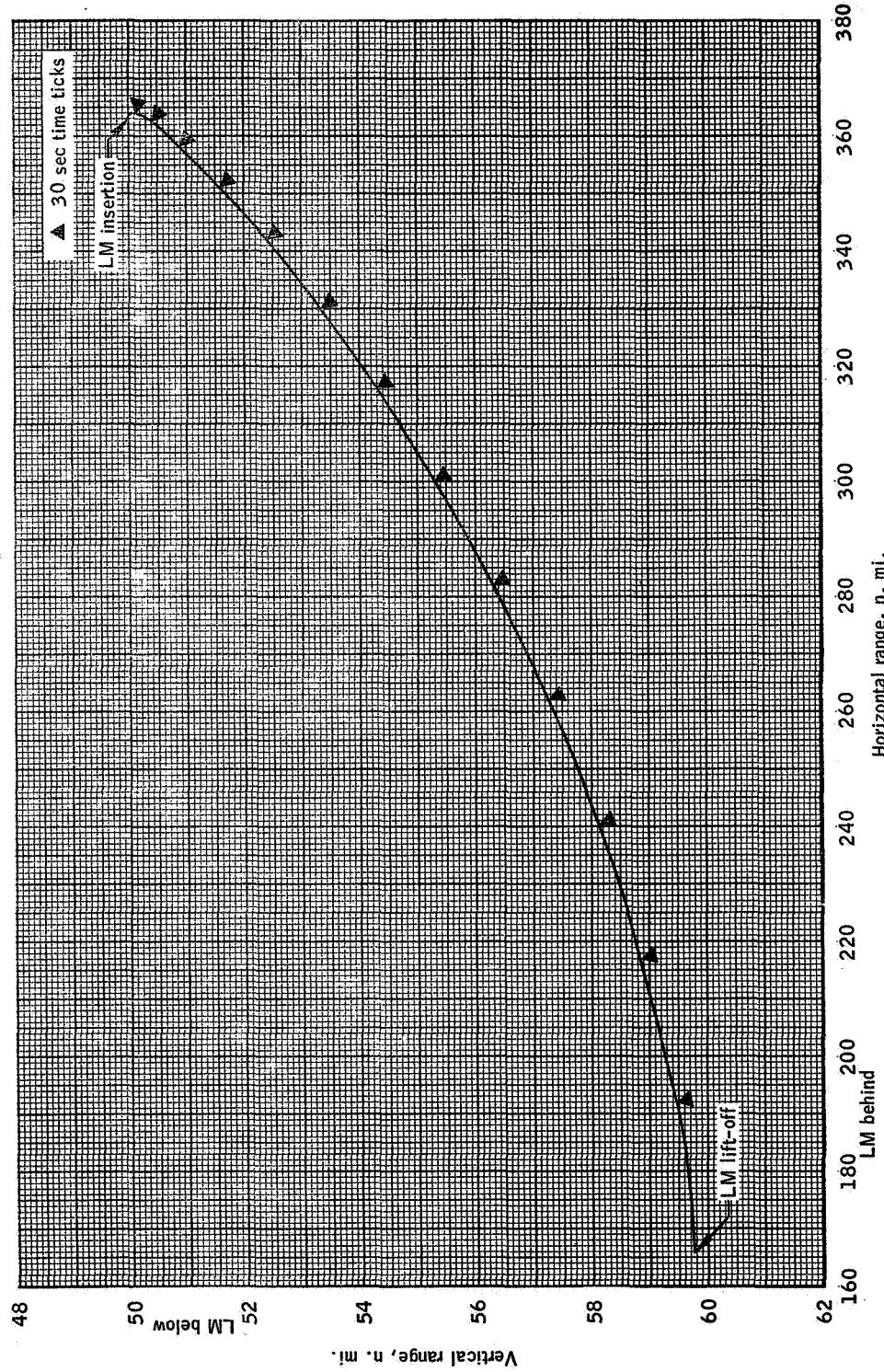
(d) LM-CSM range versus time from lunar lift-off.

Figure 4. - Continued.



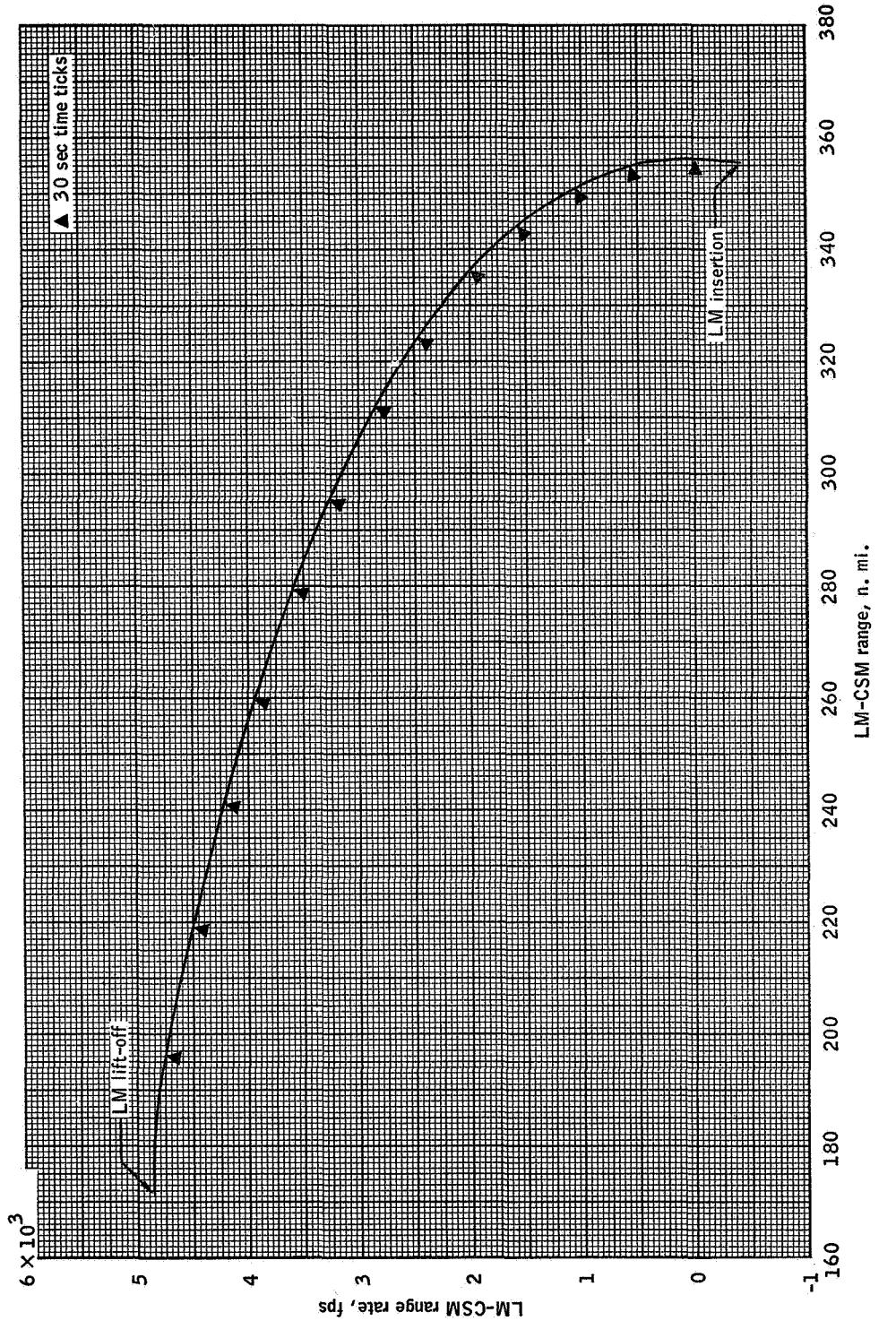
(g) LM-CSM range rate versus time from lunar lift-off.

Figure 4. - Continued.



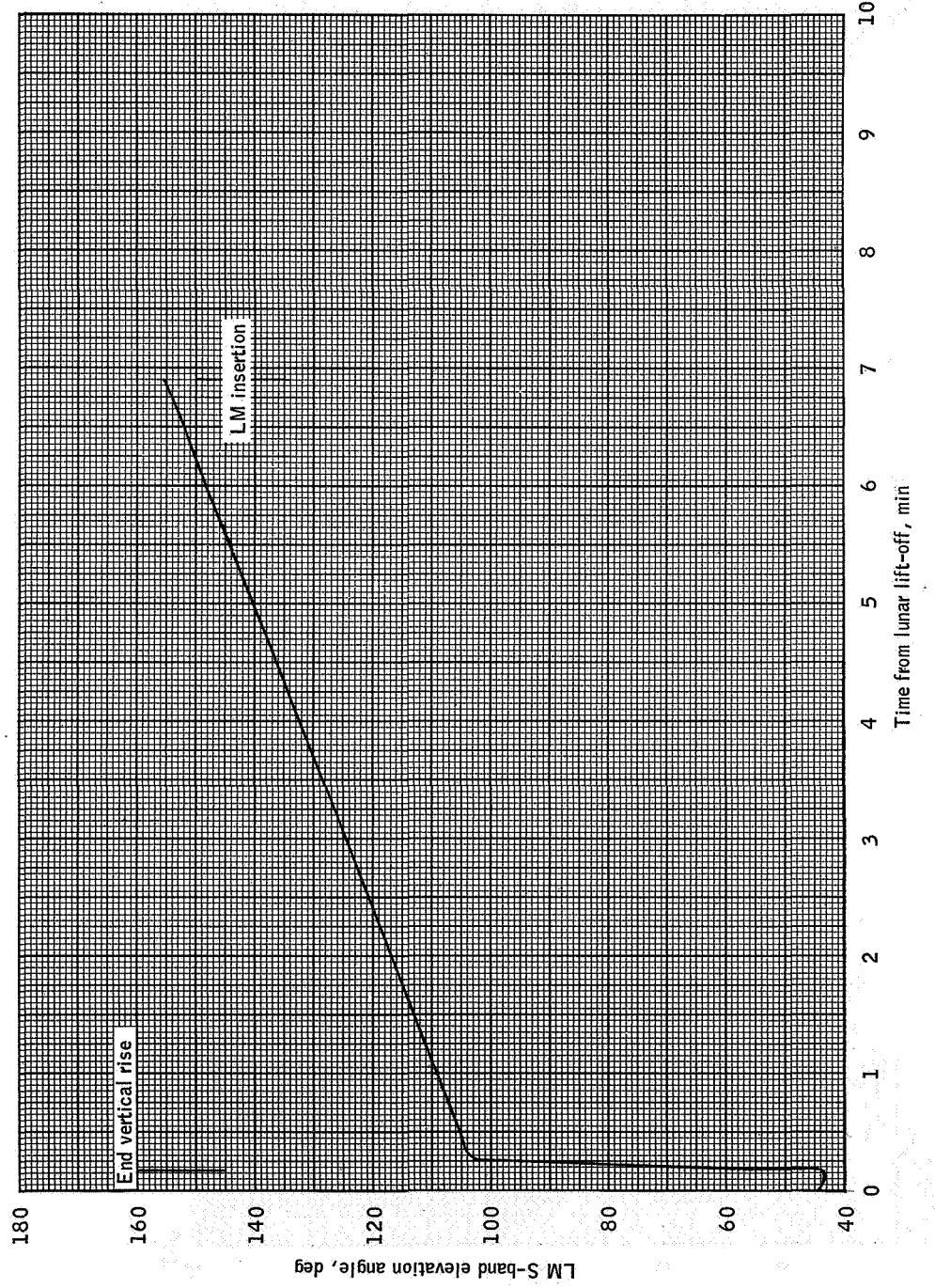
(h) Vertical range versus horizontal range (CSM referenced).

Figure 4. -- Continued.



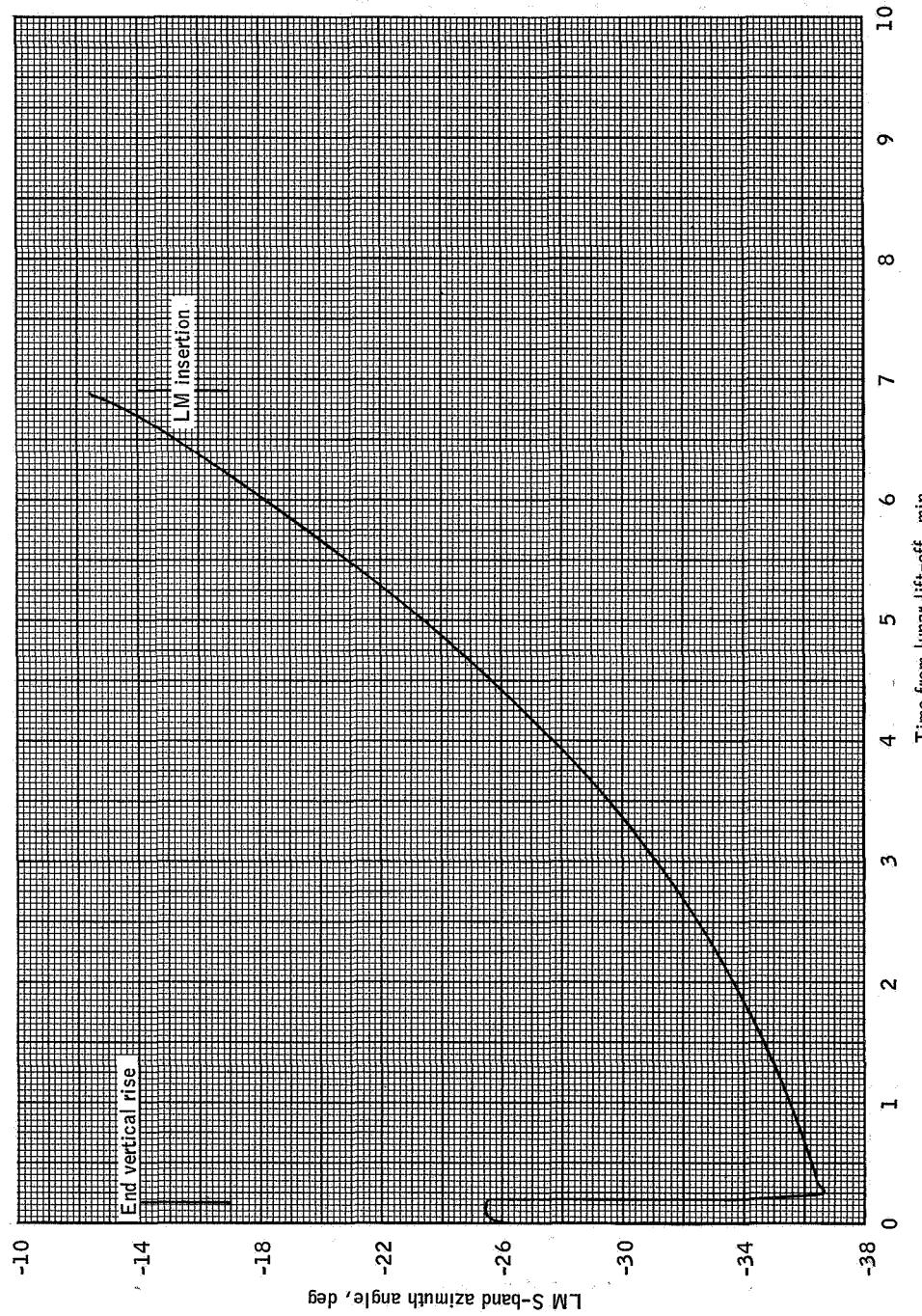
(i) LM-CSM range rate versus range.

Figure 4.- Continued.



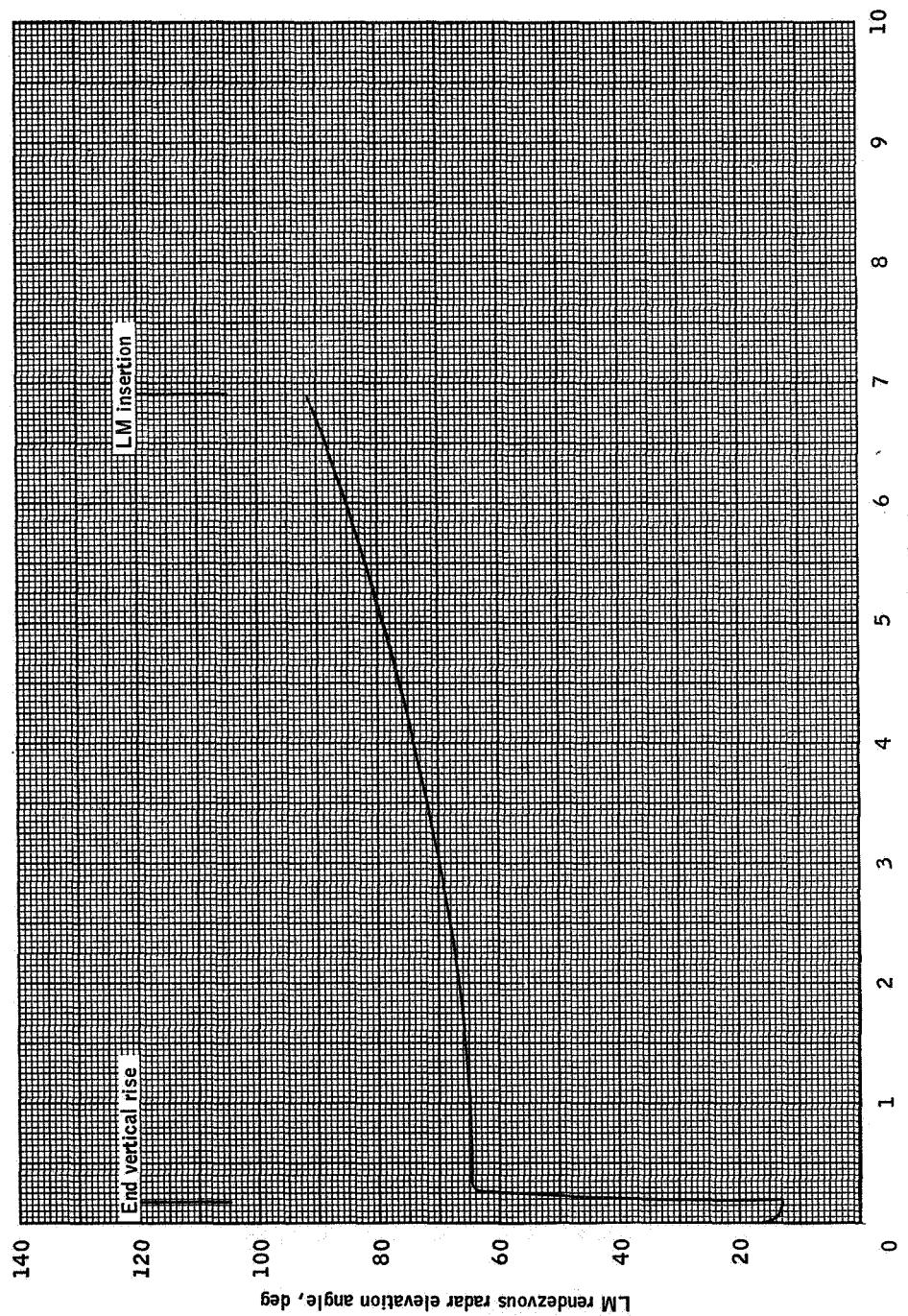
(j) LM S-band elevation angle versus time from lunar lift-off.

Figure 4.- Continued.



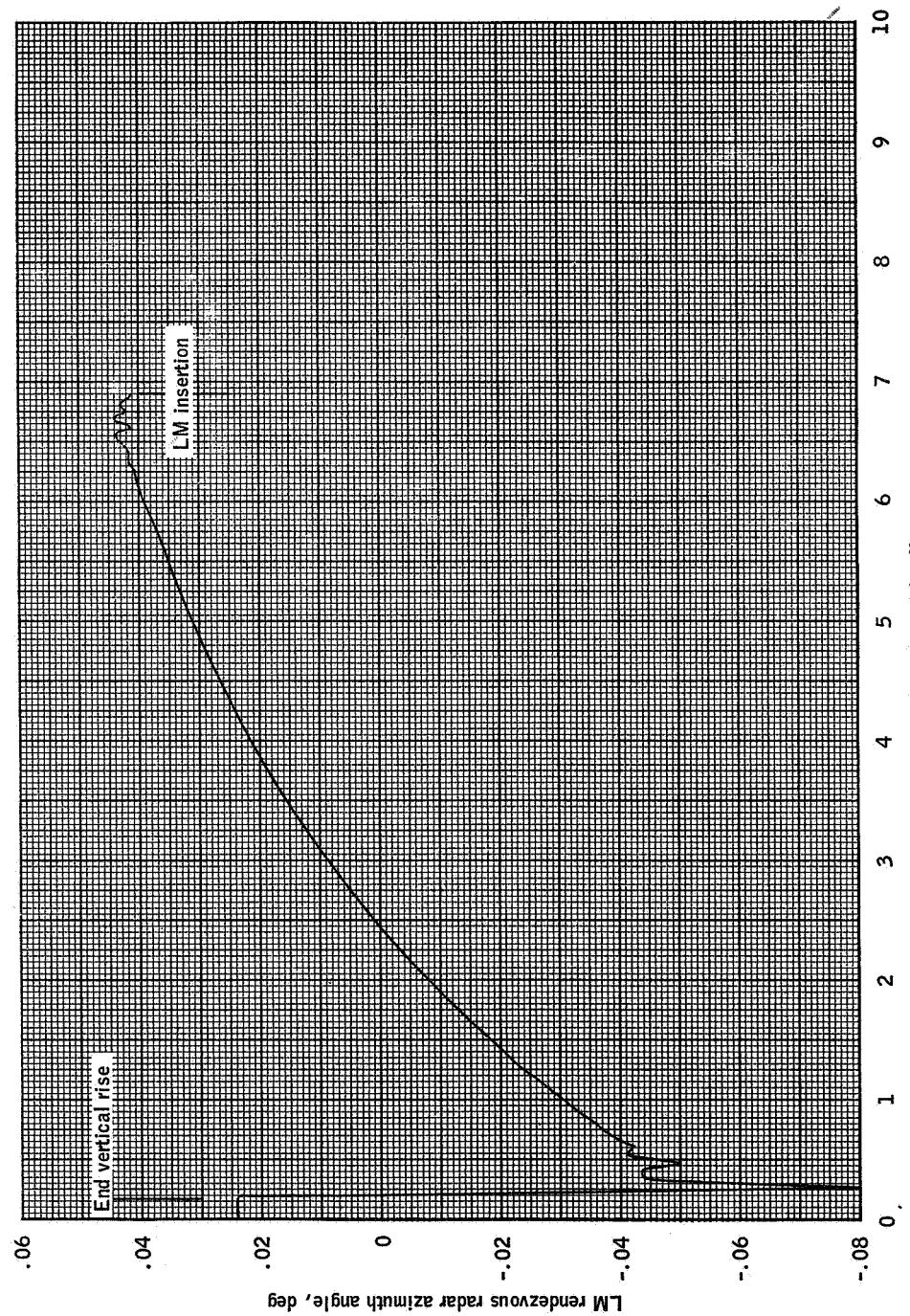
(k) LM S-band azimuth angle versus time from lunar lift-off.

Figure 4.- Continued.



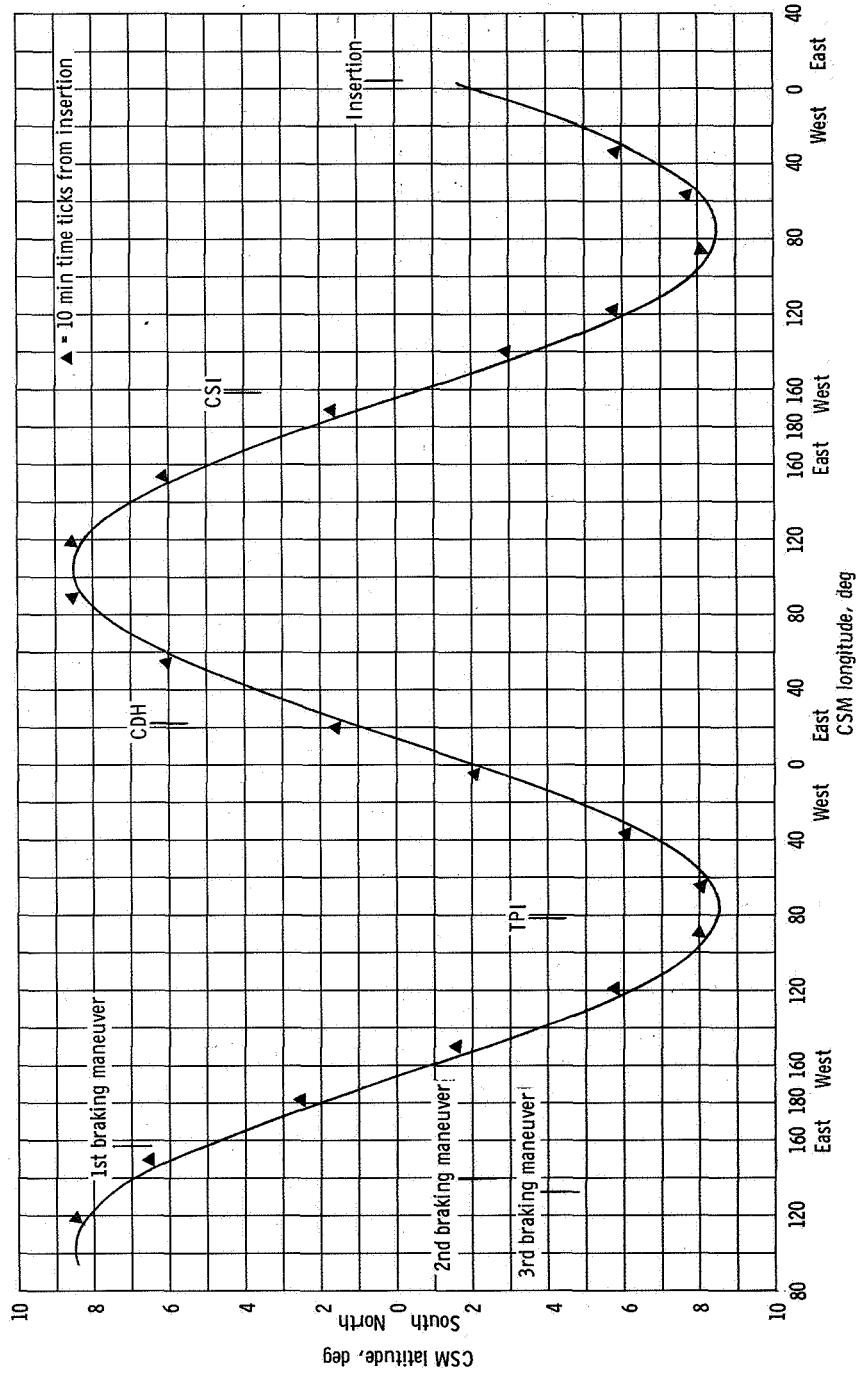
(d) LM rendezvous radar elevation angle versus time from lunar lift-off.

Figure 4.- Continued.



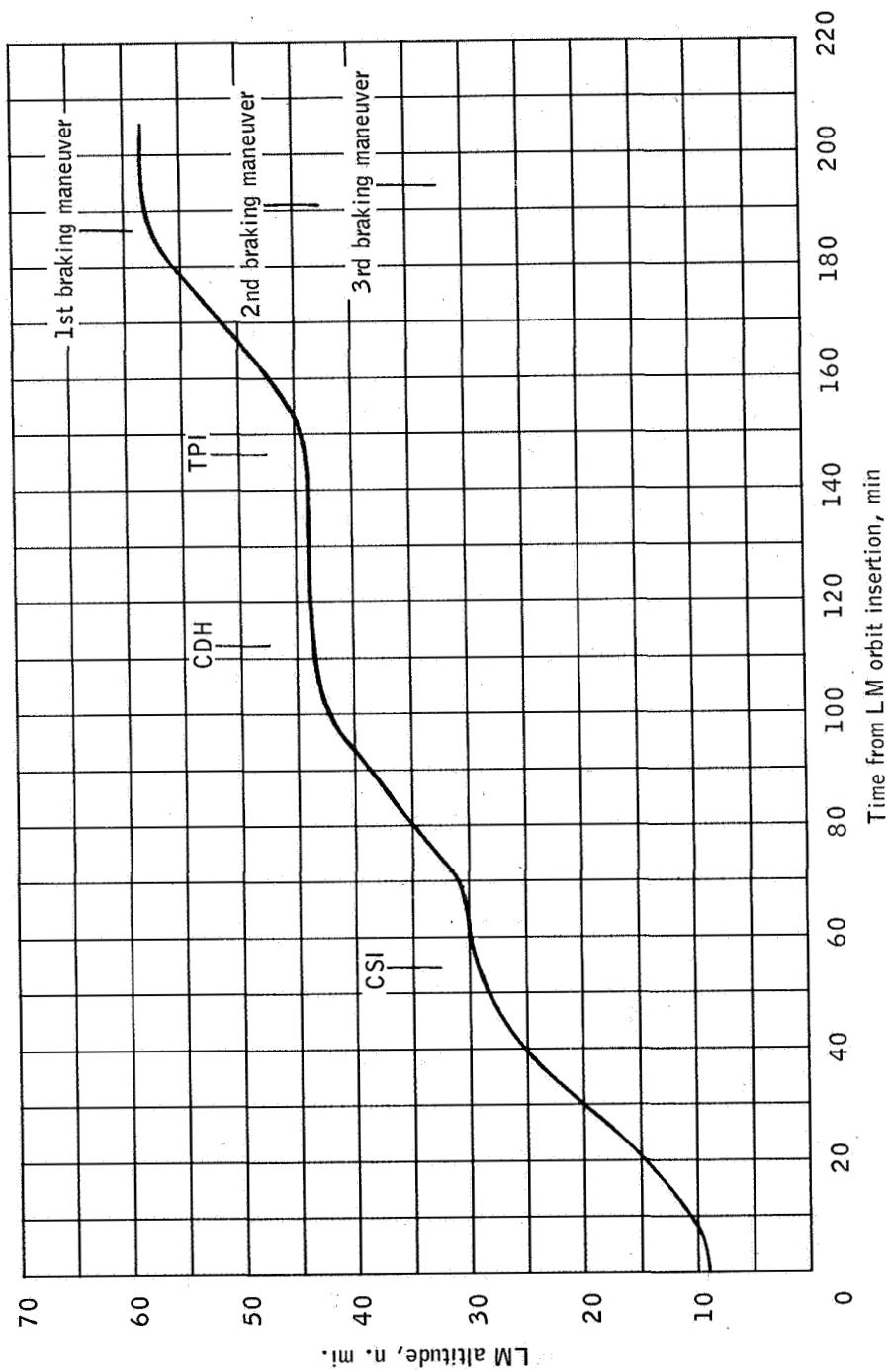
(m) LM rendezvous radar azimuth angle versus time from lunar lift-off.

Figure 4.- Concluded.



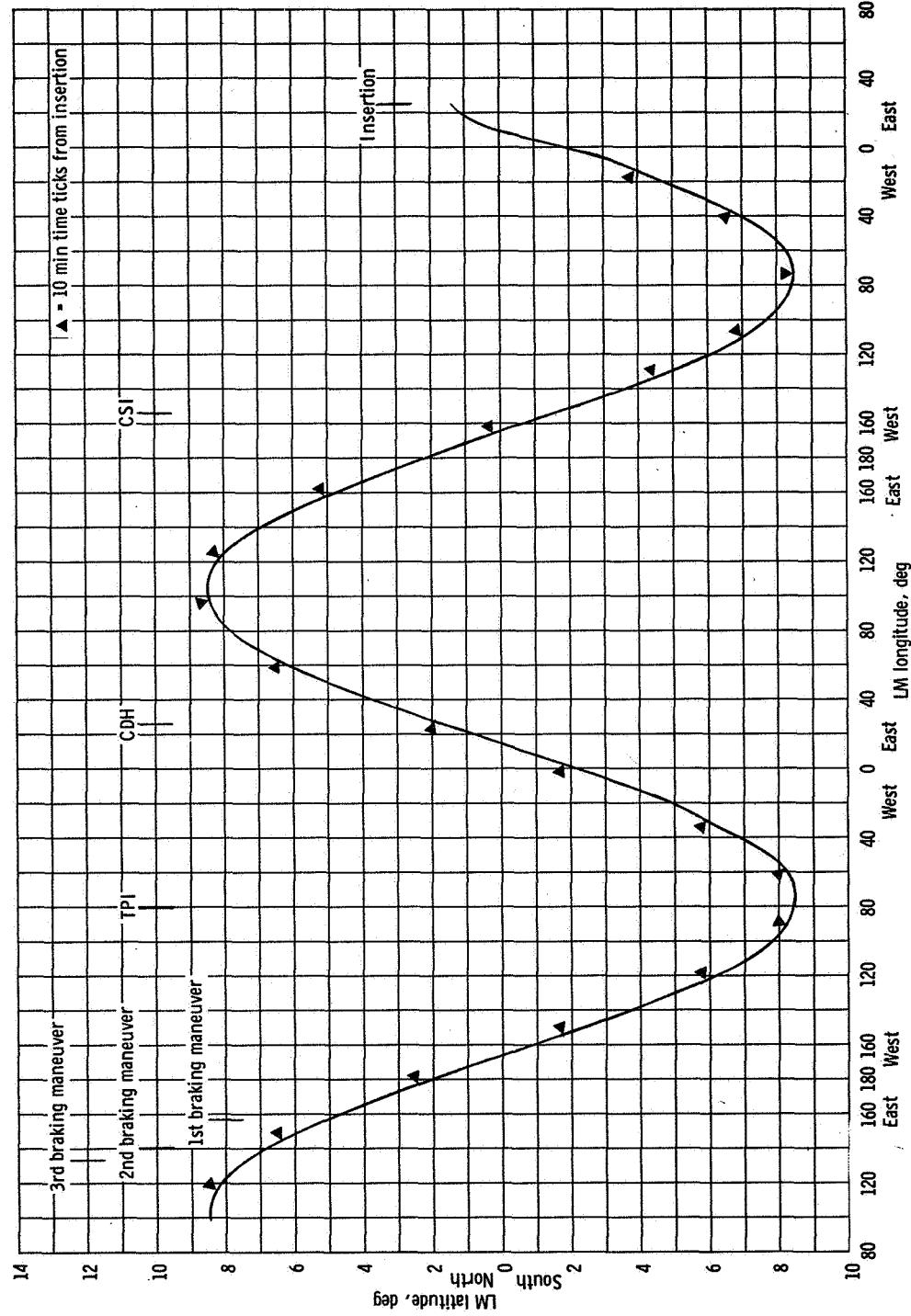
(a) CSM latitude versus CSM longitude.

Figure 5. - Parameters from LM orbit insertion through terminal rendezvous.



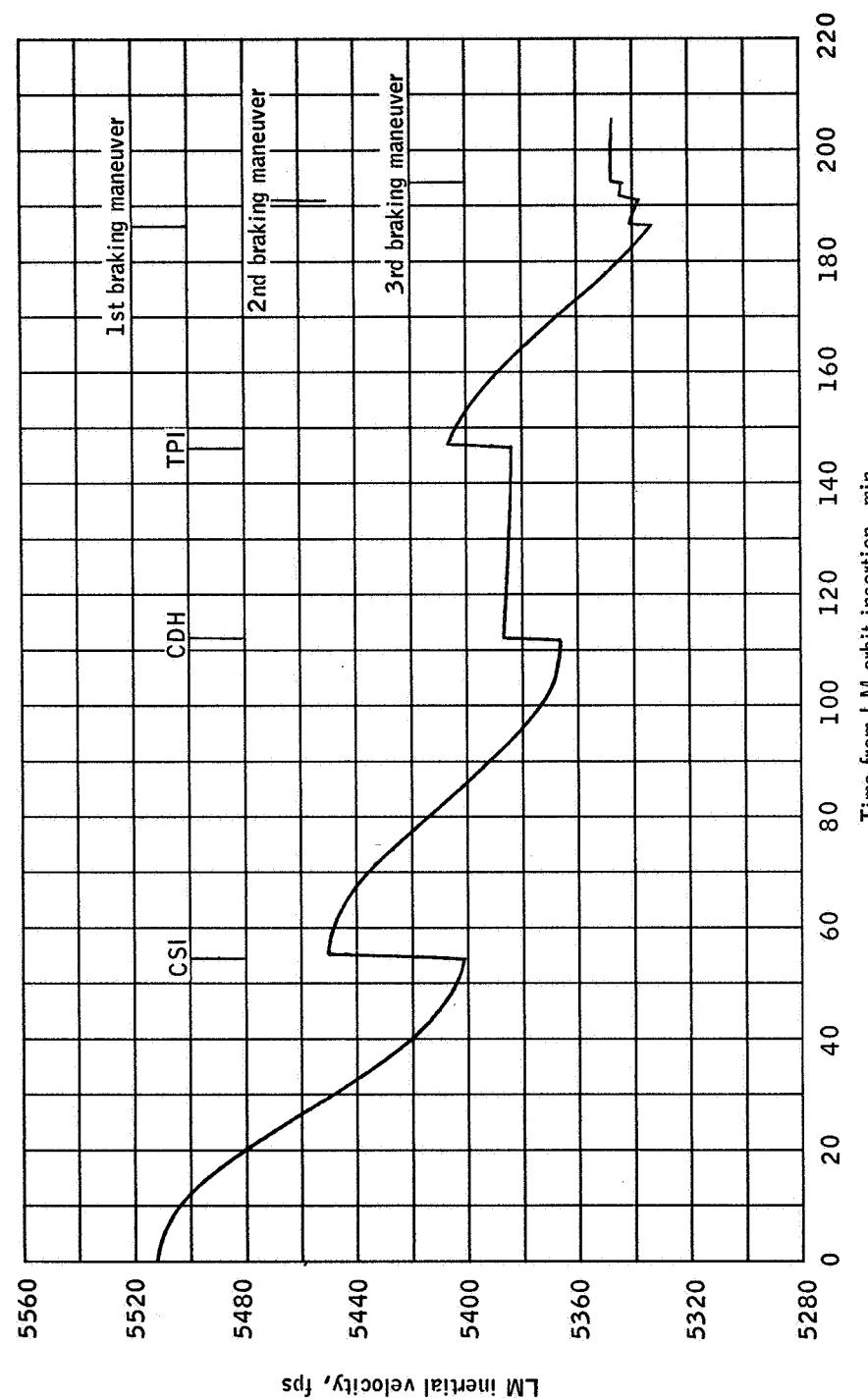
(b) LM altitude versus time from LM orbit insertion.

Figure 5.- Continued.



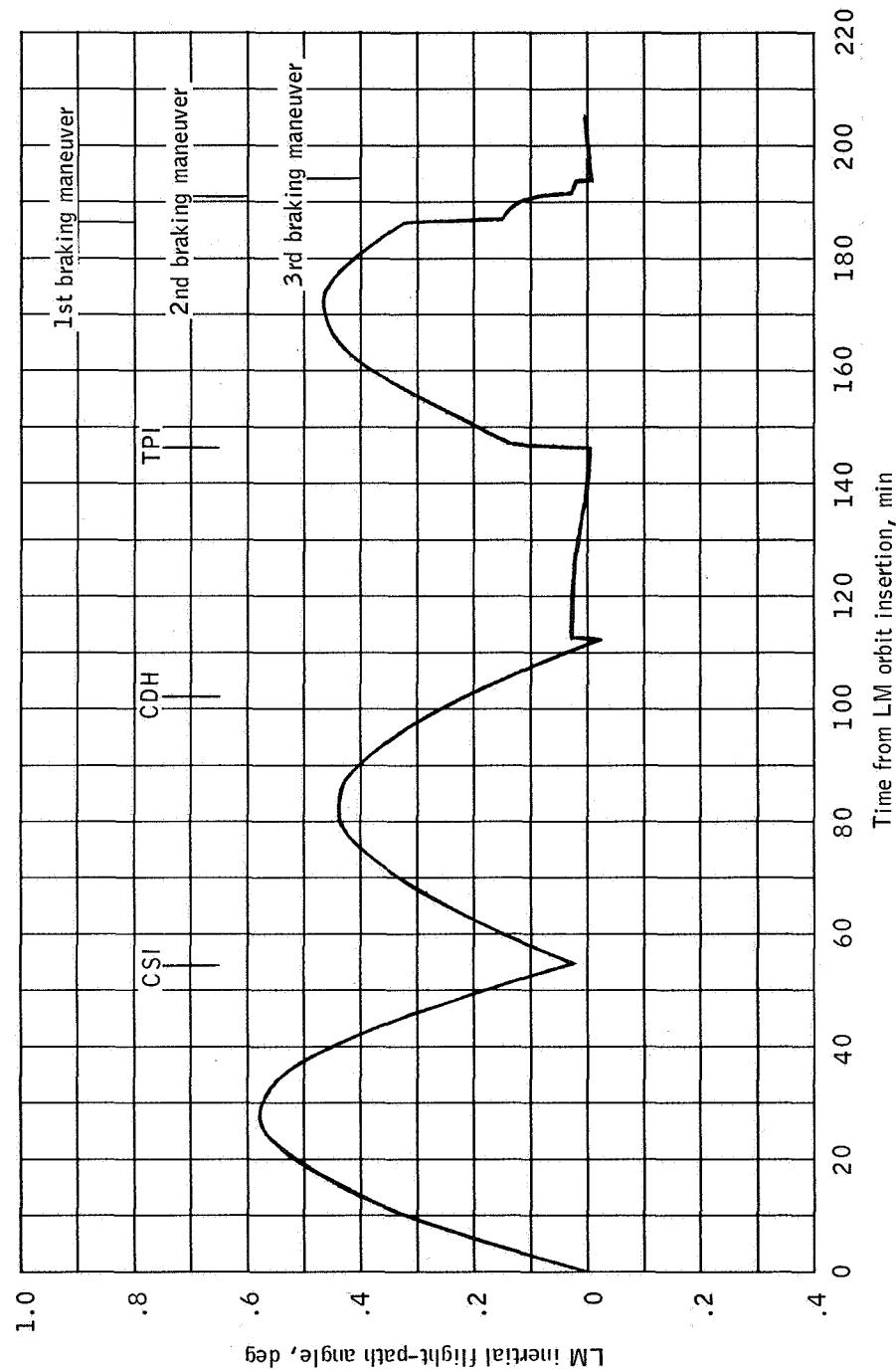
(c) LM latitude versus LM longitude.

Figure 5. – Continued.



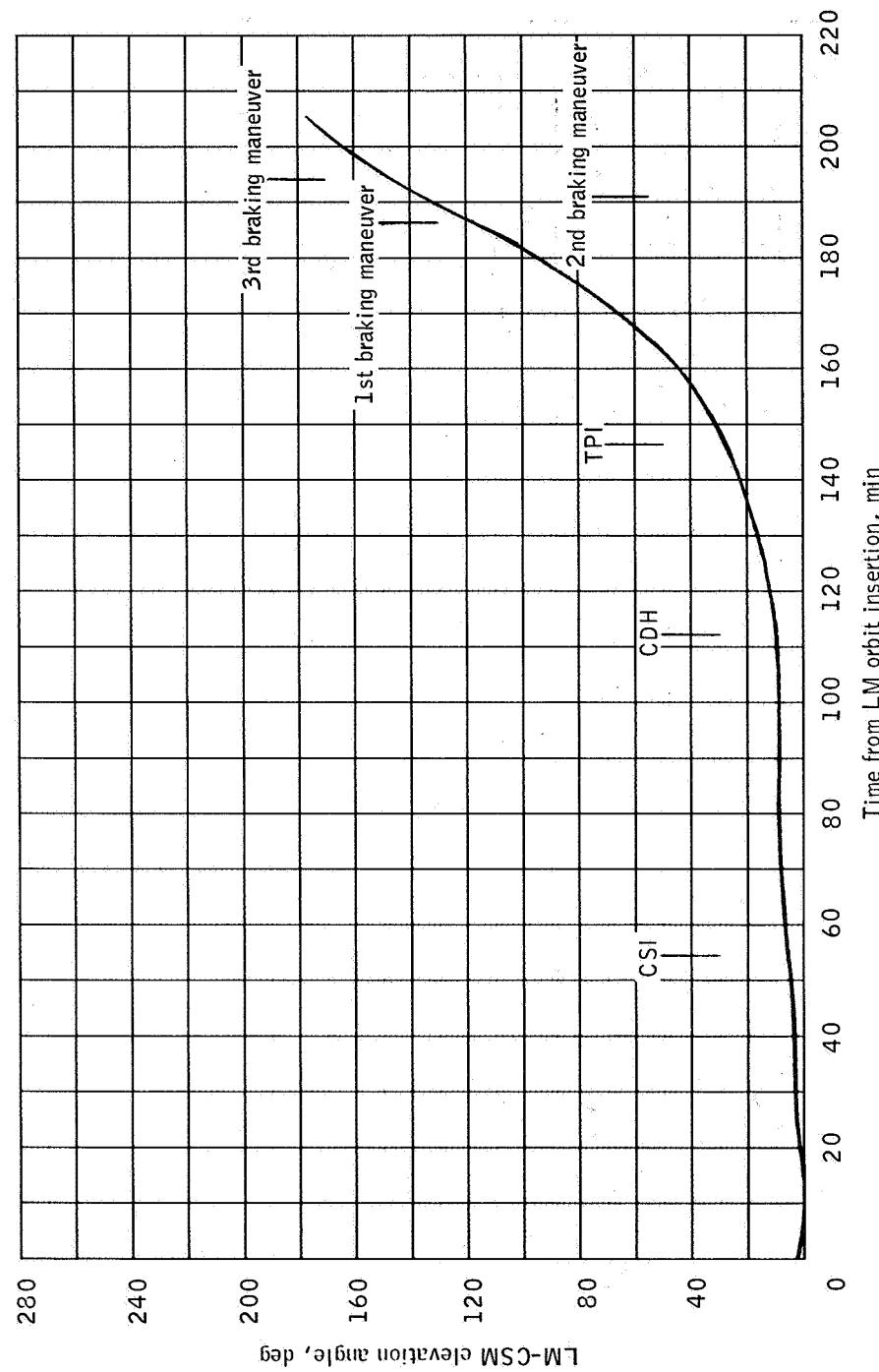
(d) LM inertial velocity versus time from LM orbit insertion.

Figure 5. - Continued.



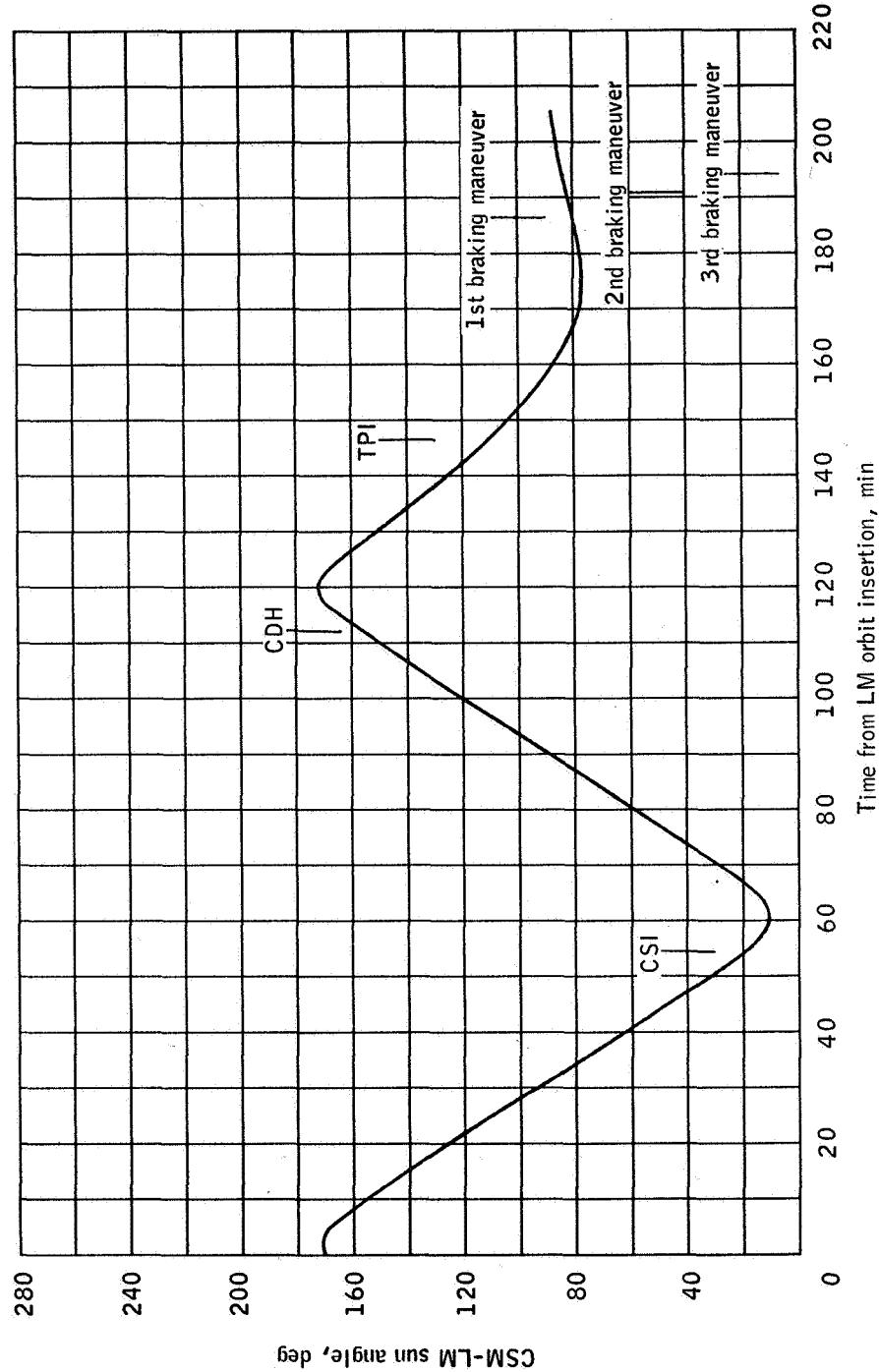
(e) LM inertial flight-path angle versus time from LM orbit insertion.

Figure 5. - Continued.



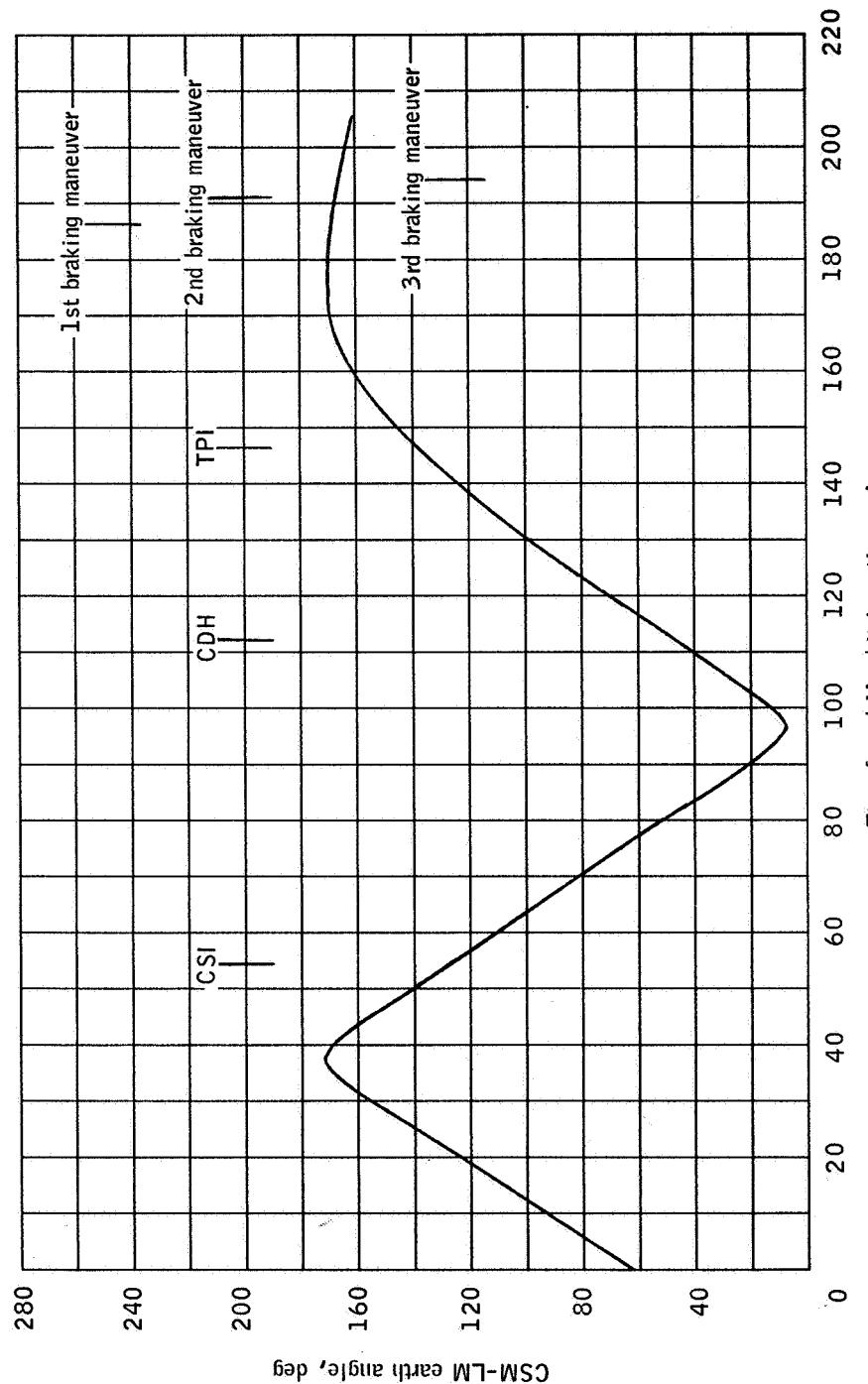
(f) LM-CSM elevation angle versus time from LM orbit insertion.

Figure 5.- Continued.



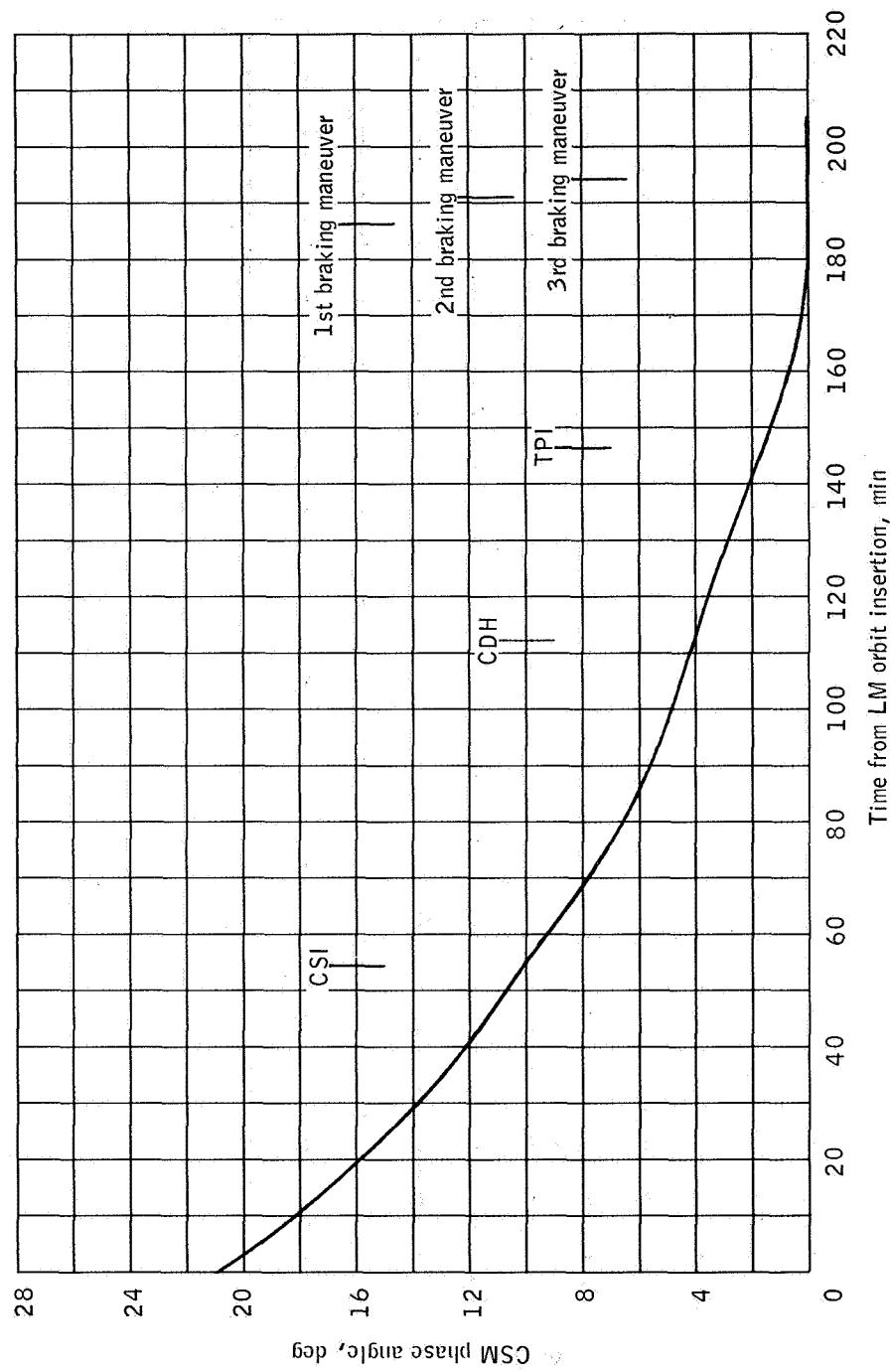
(g) CSM-LM-sun angle versus time from LM orbit insertion.

Figure 5. - Continued.



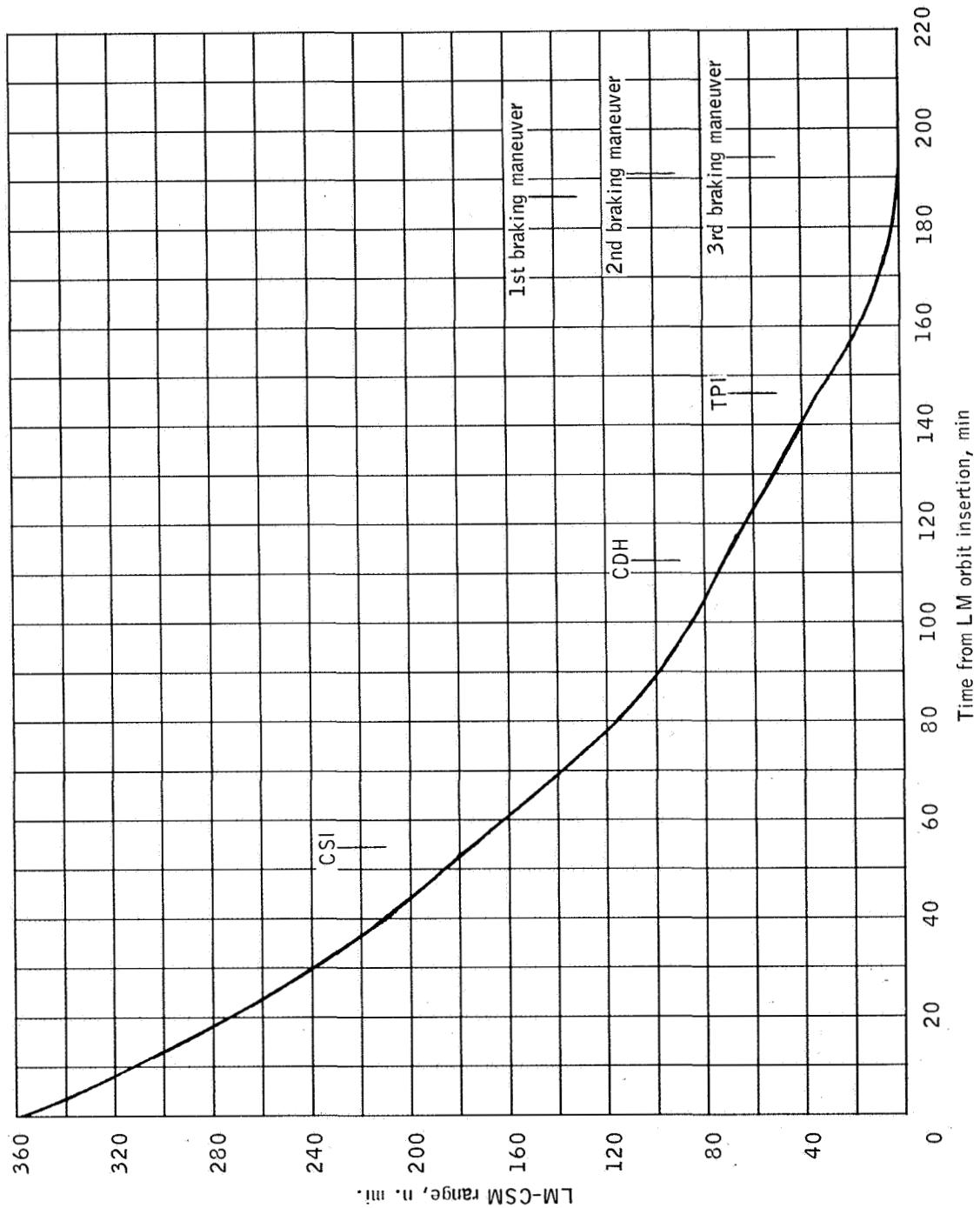
(h) CSM-LM-earth angle versus time from LM orbit insertion.

Figure 5. - Continued.



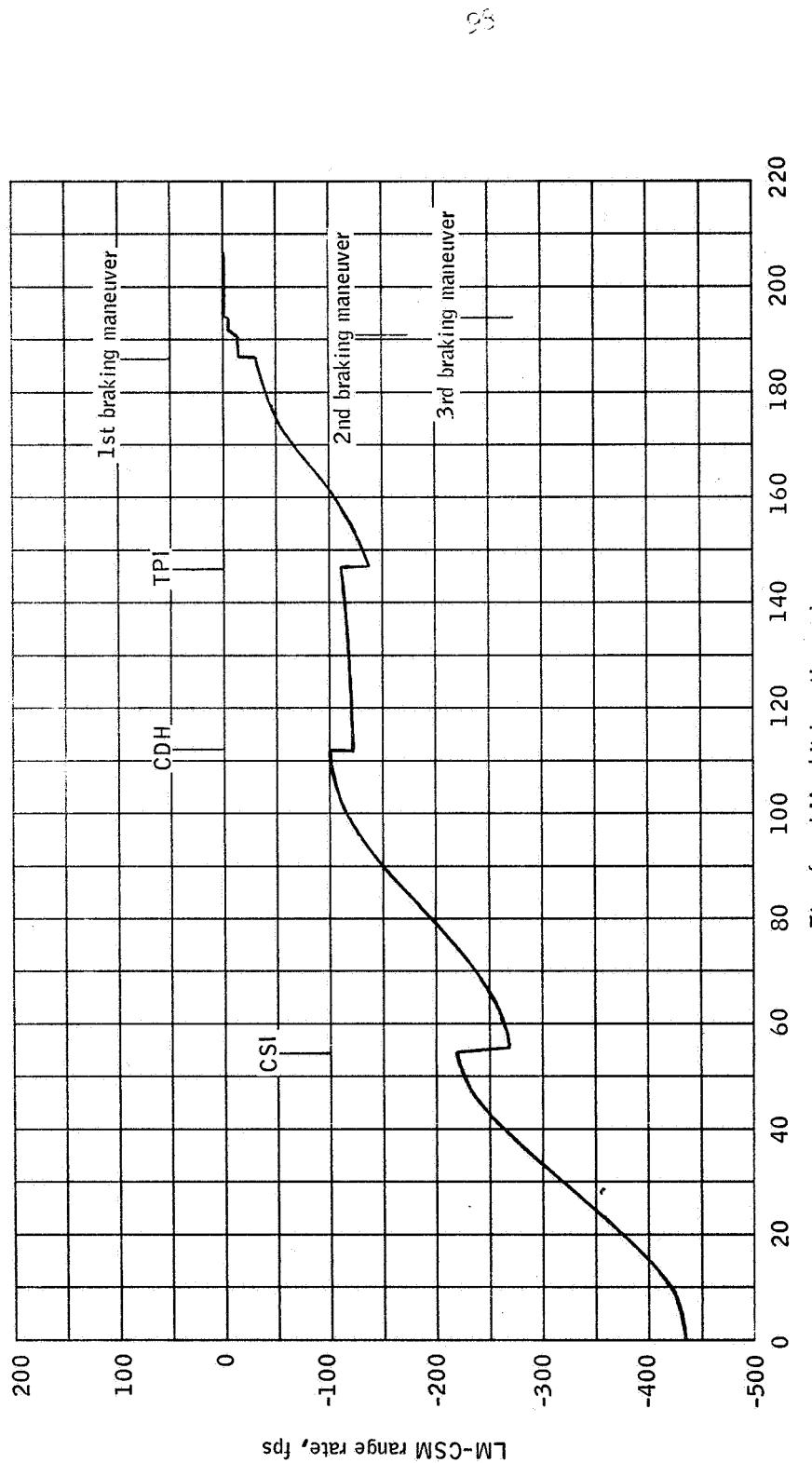
(i) CSM phase angle versus time from LM orbit insertion.

Figure 5. - Continued.



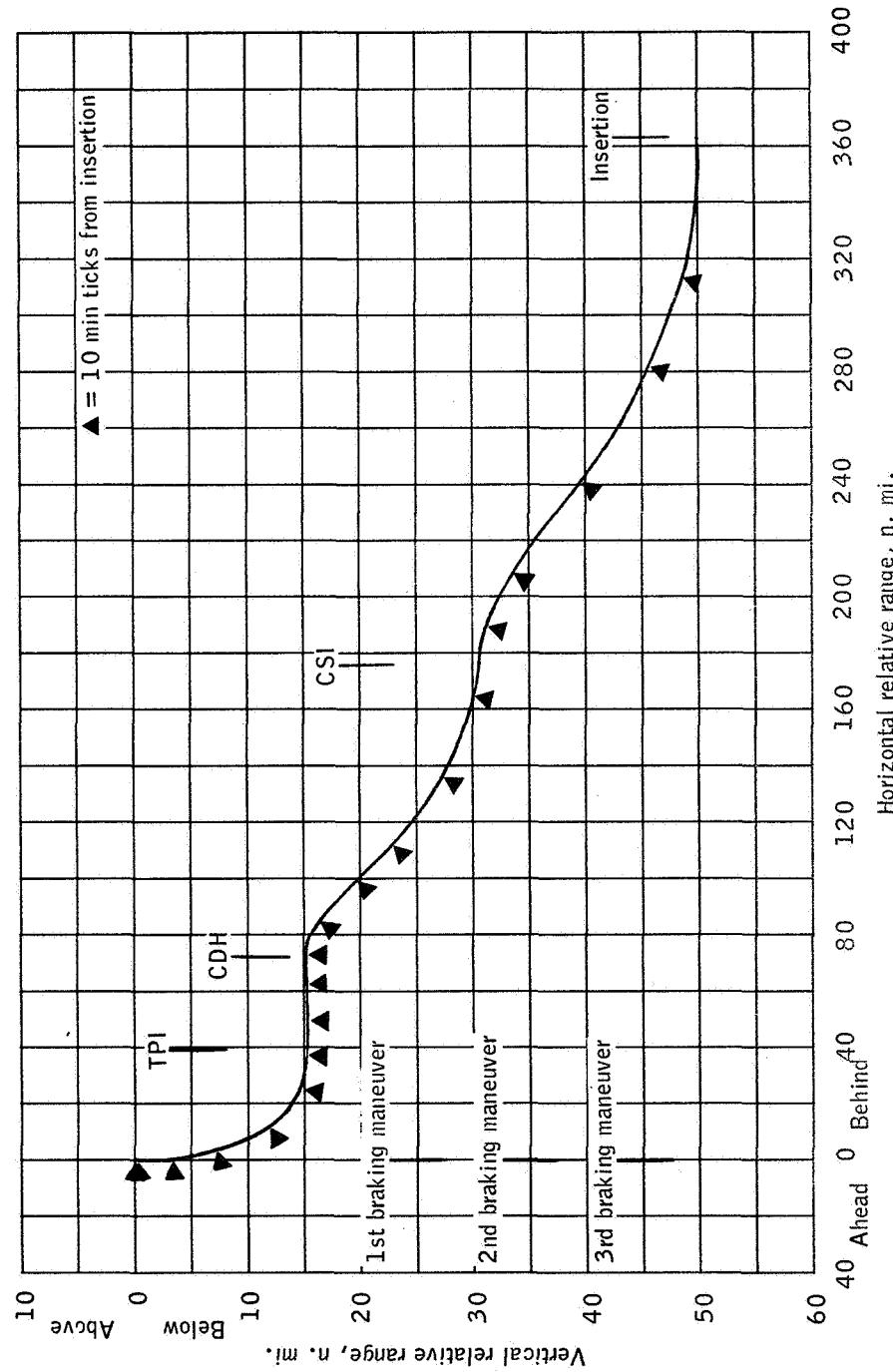
(j) LM-CSM range versus time from LM orbit insertion.

Figure 5. - Continued.



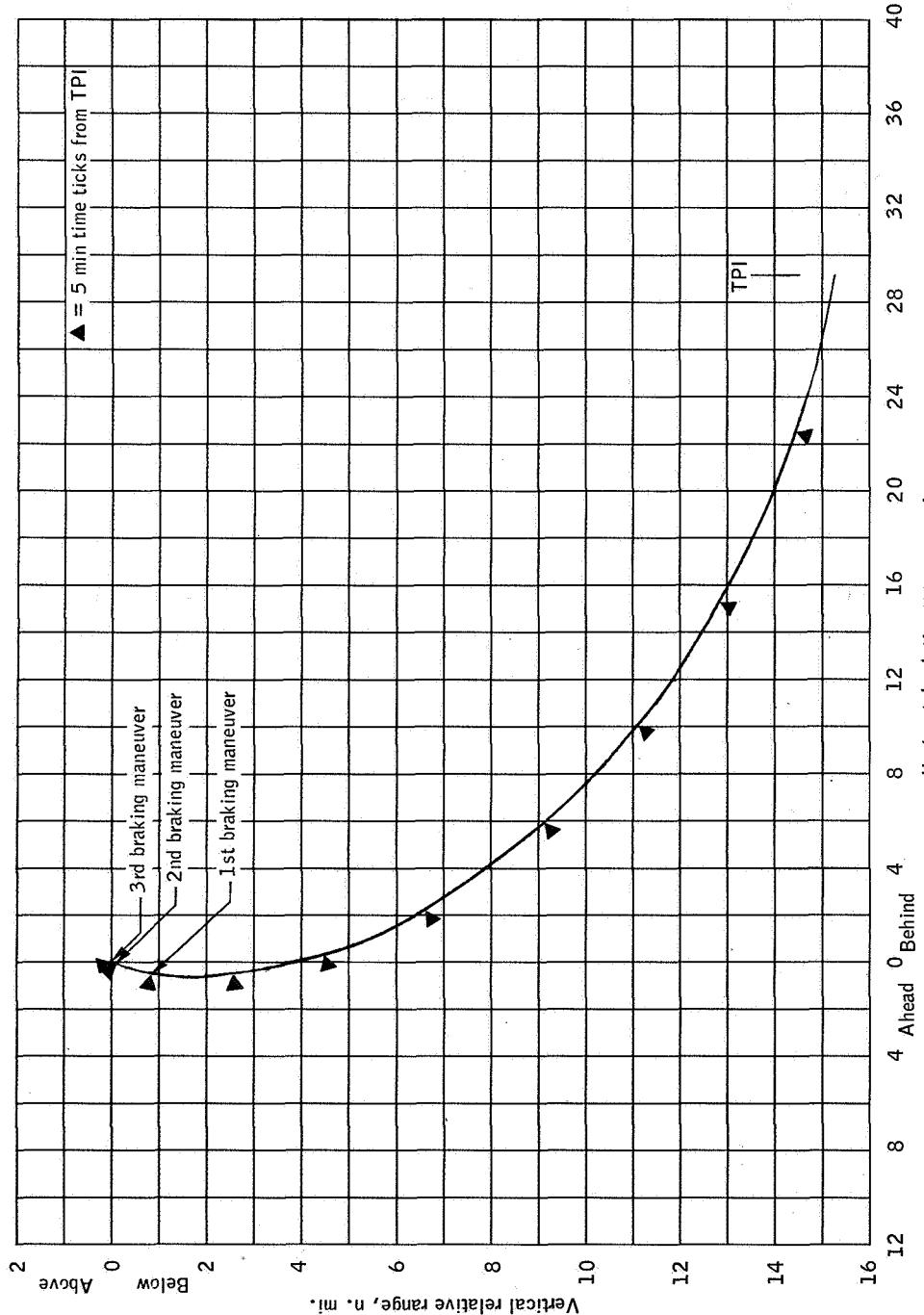
(k) LM-CSM range rate versus time from LM orbit insertion.

Figure 5. - Continued.



(I) Vertical relative range versus horizontal relative range.

Figure 5. - Continued.



(m) Vertical relative range versus horizontal relative range from TPI through terminal rendezvous.

Figure 5. - Concluded.

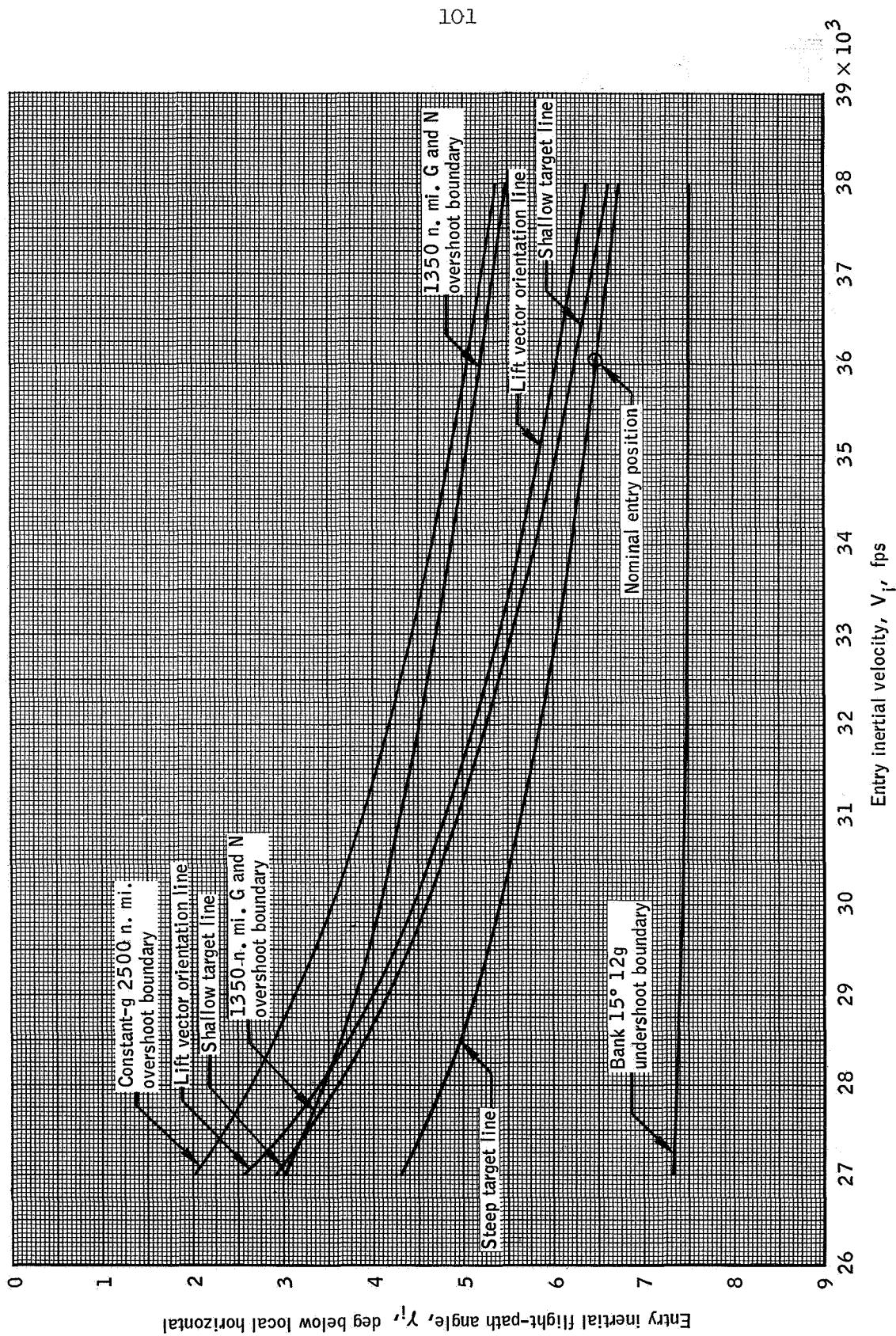


Figure 6.- Entry corridor.

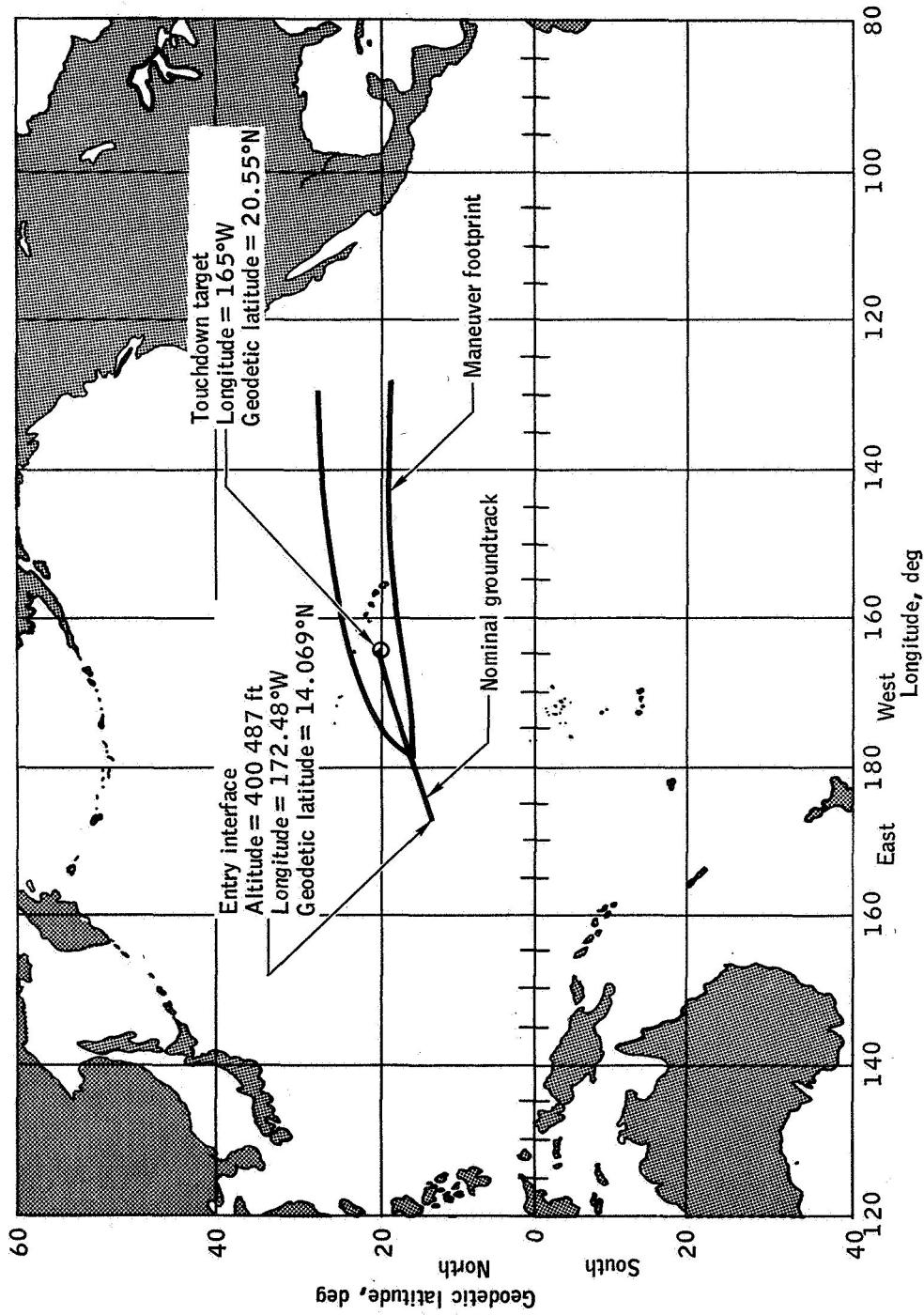


Figure 7. - Maneuver footprint and nominal ground track.

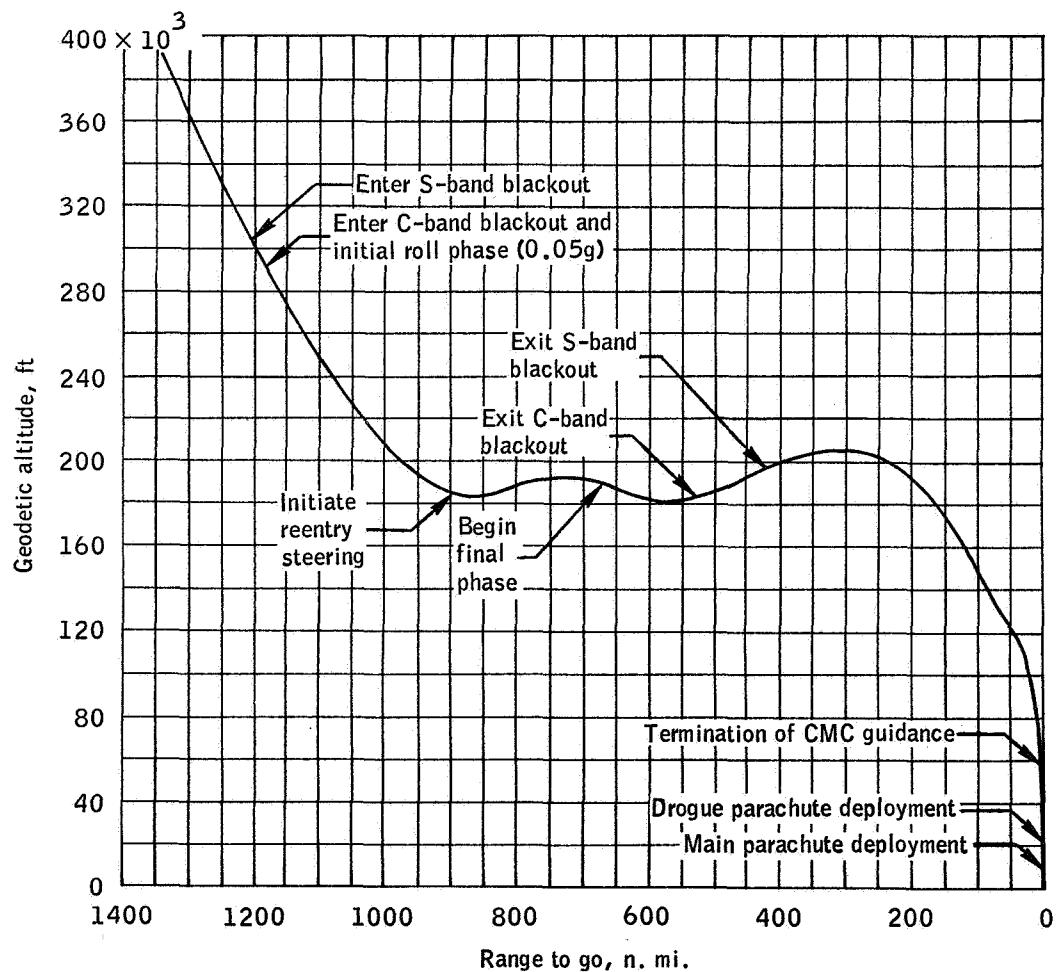


Figure 8.- Geodetic altitude versus range to go.

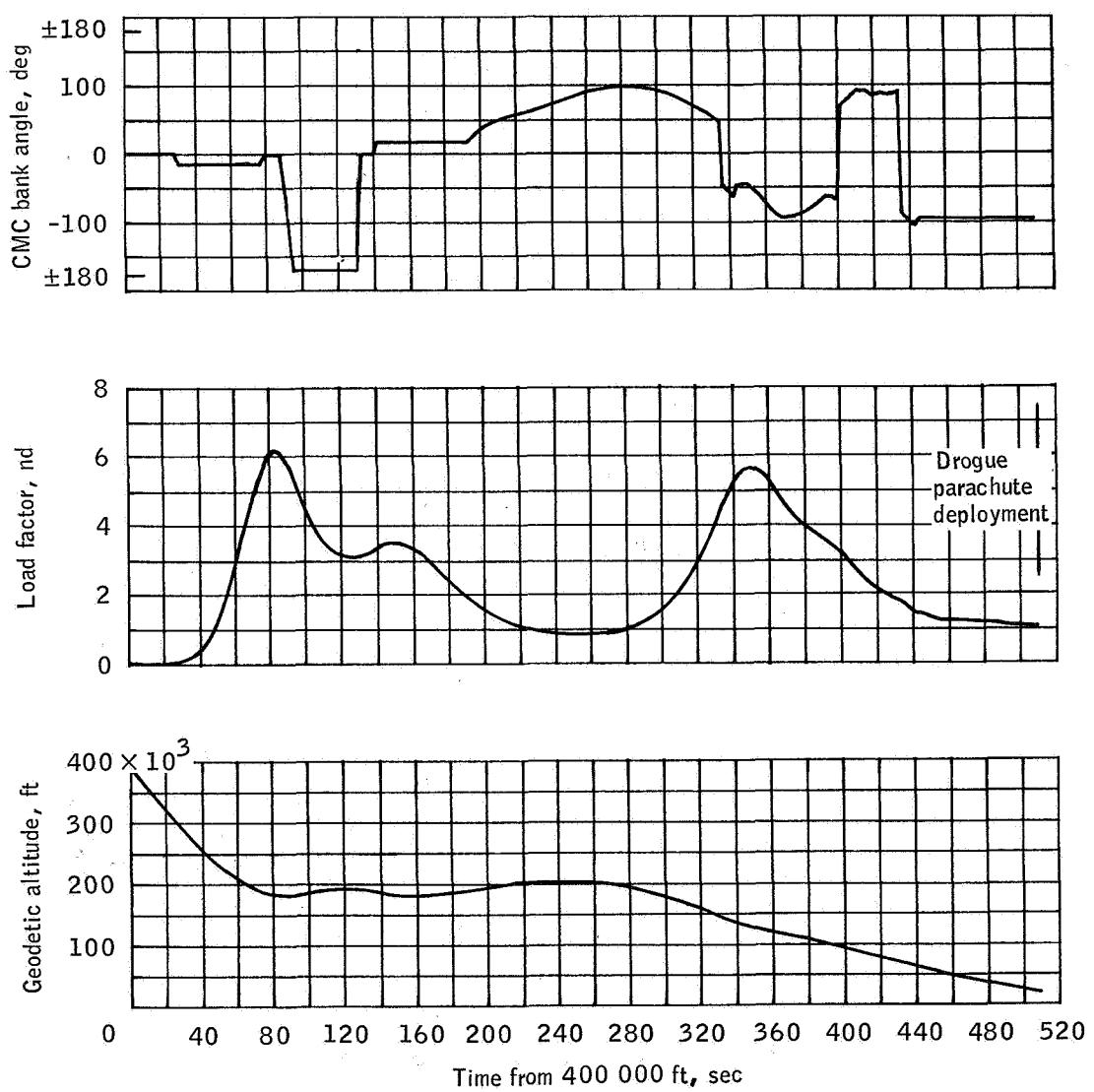


Figure 9.- CMC commanded bank angle, load factor, and altitude time histories.

$10^5$

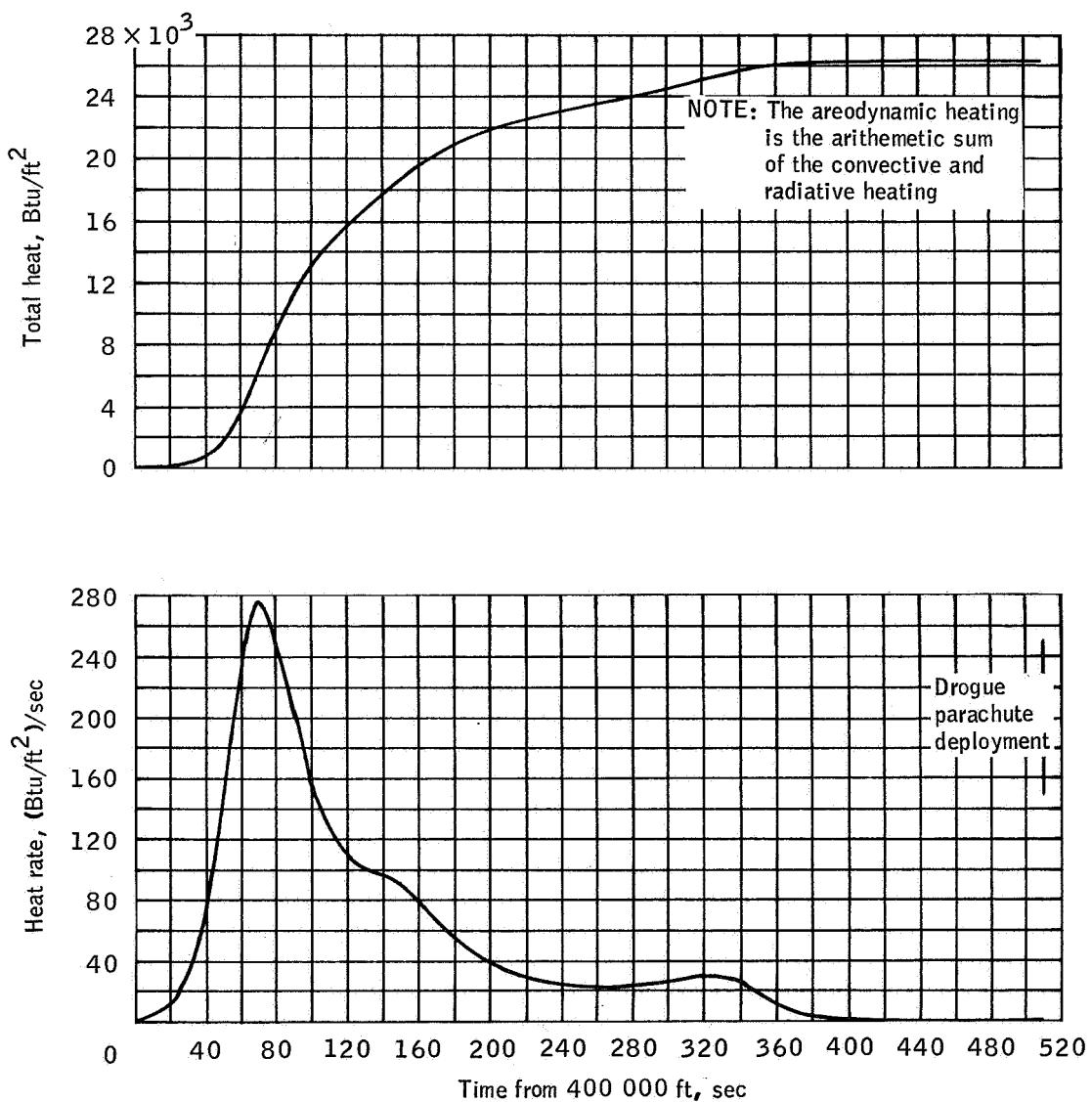
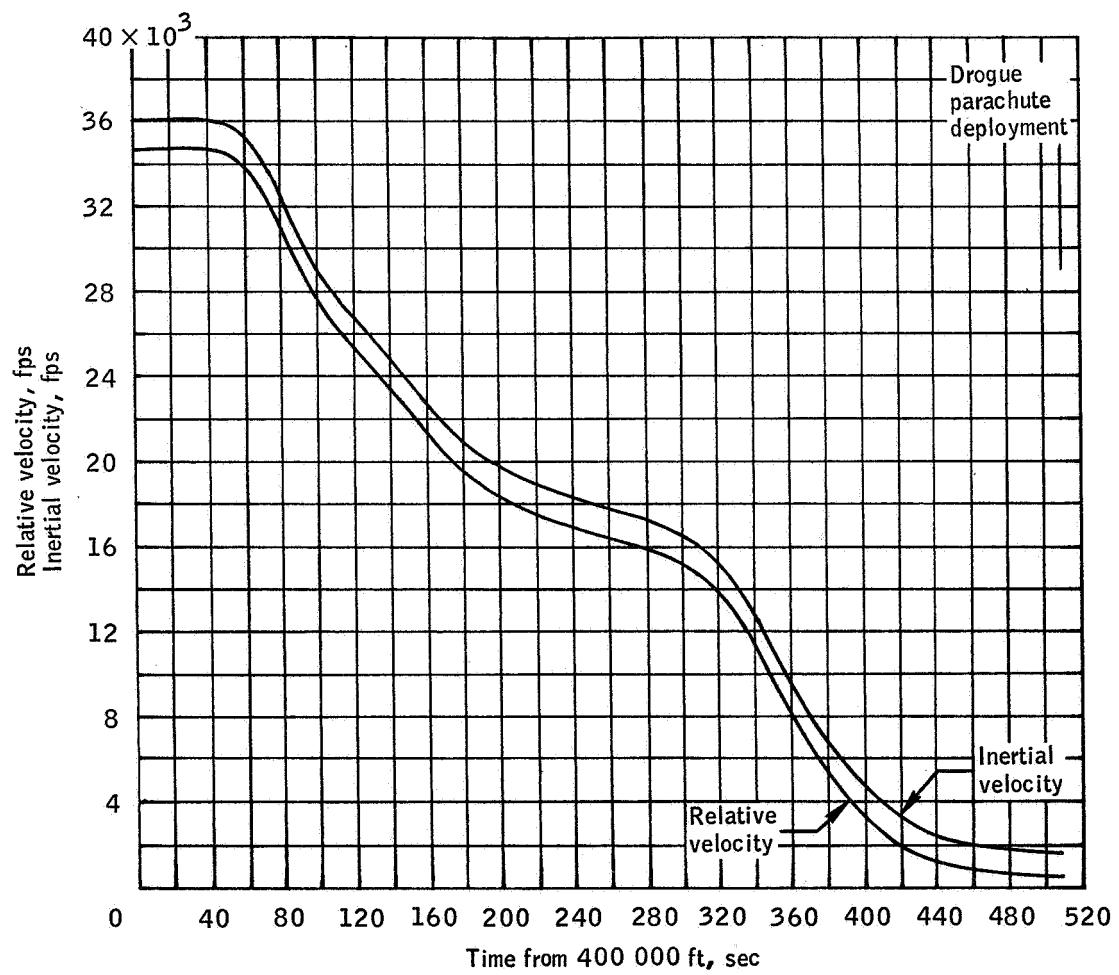
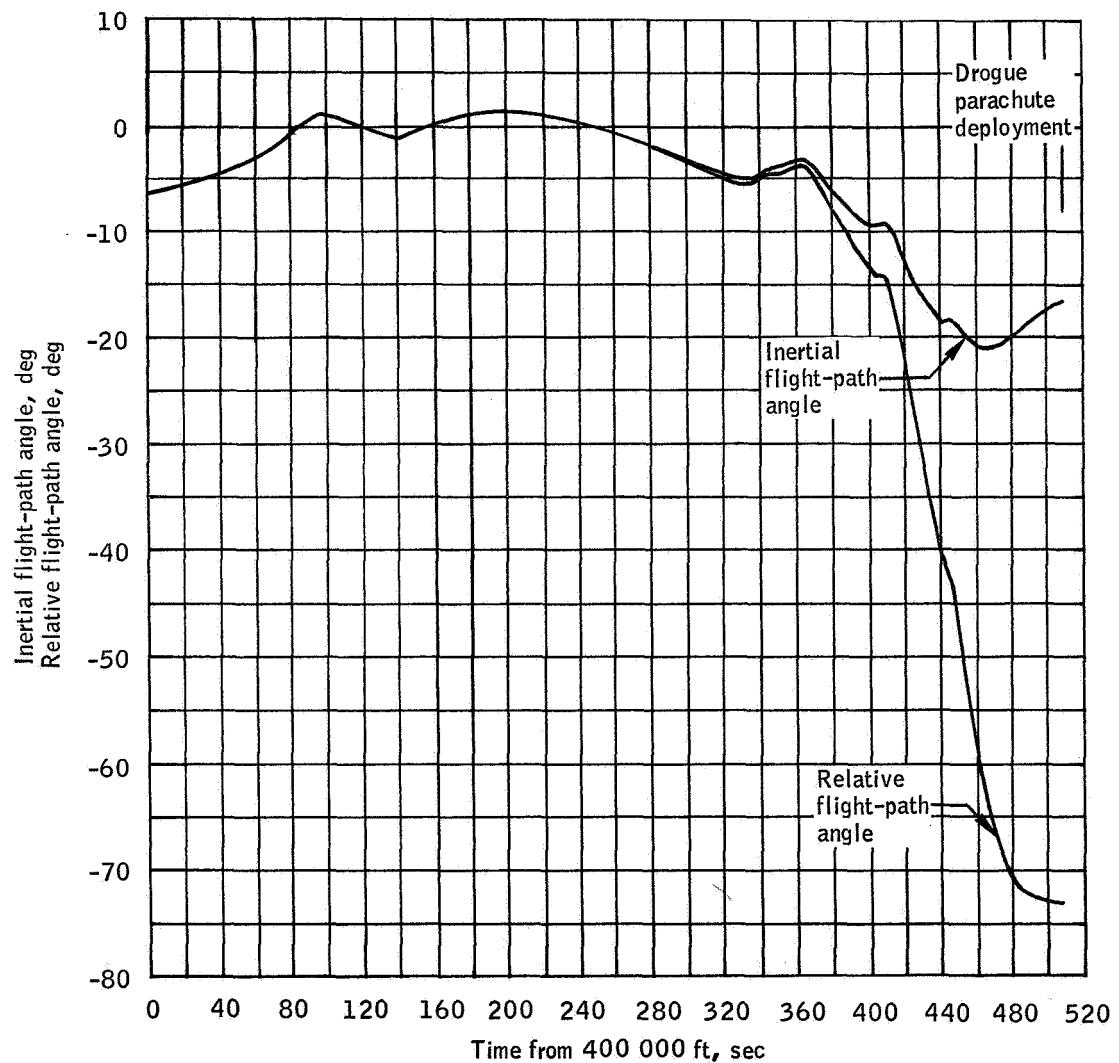


Figure 10.- Aerodynamic heating rate and heat load time histories.



(a) Relative and inertial velocity

Figure 11.- Time histories of velocity and flight-path angle for reentry.



(b) Relative and inertial flight-path angle

Figure 11.- Concluded.

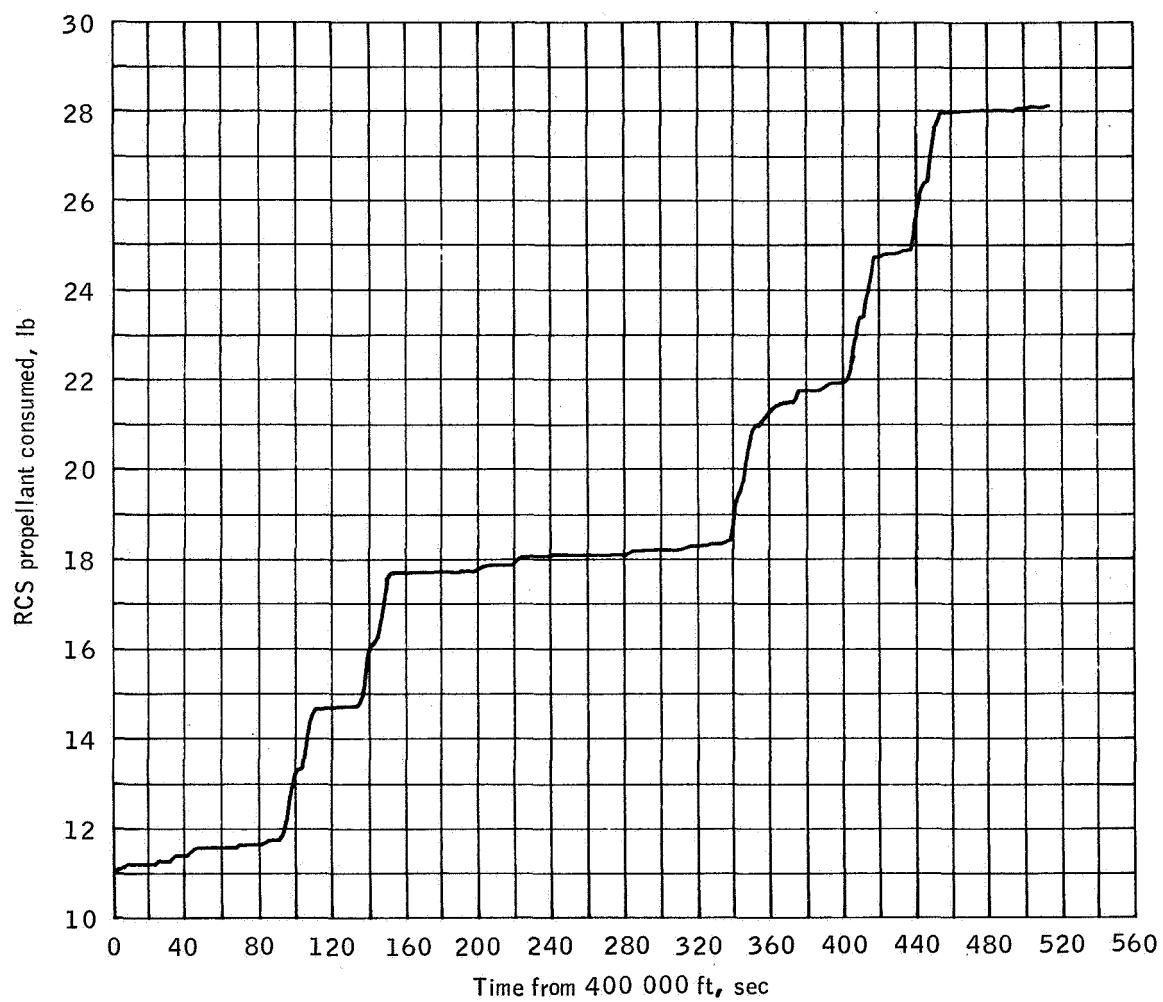


Figure 12.- Total RCS propellant consumed from separation.

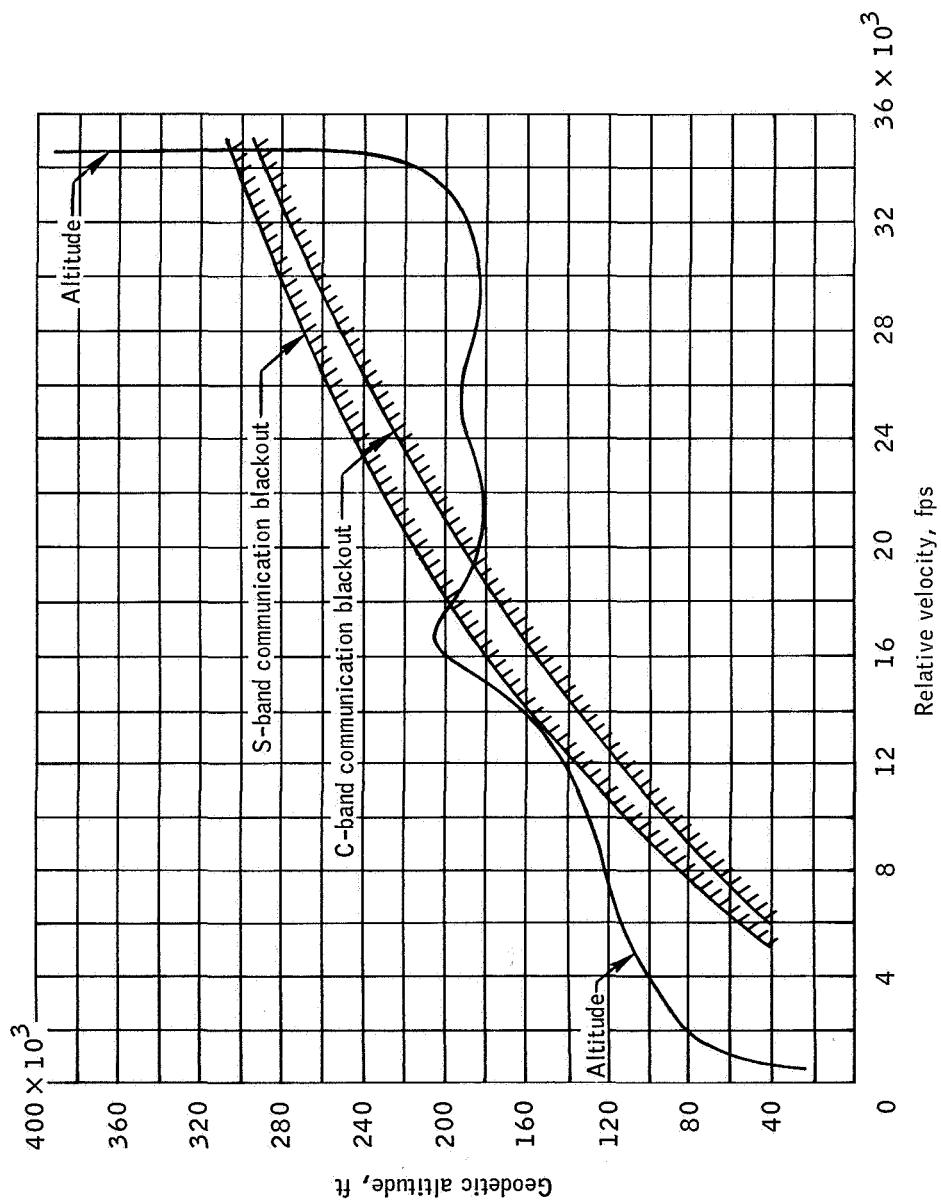


Figure 13.—Communications blackout.

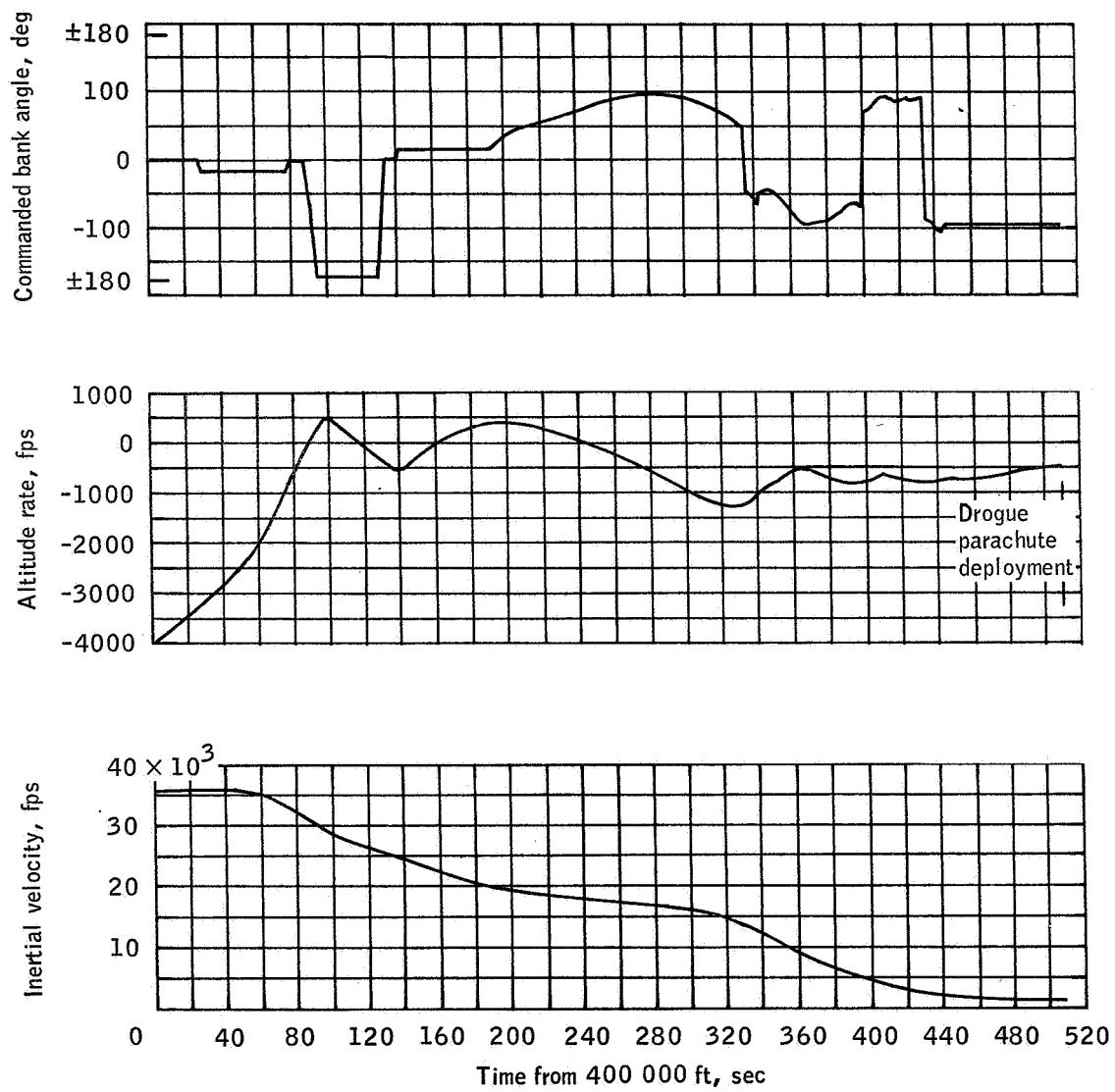


Figure 14.- CMC commanded bank angle, altitude rate and inertial velocity time histories.

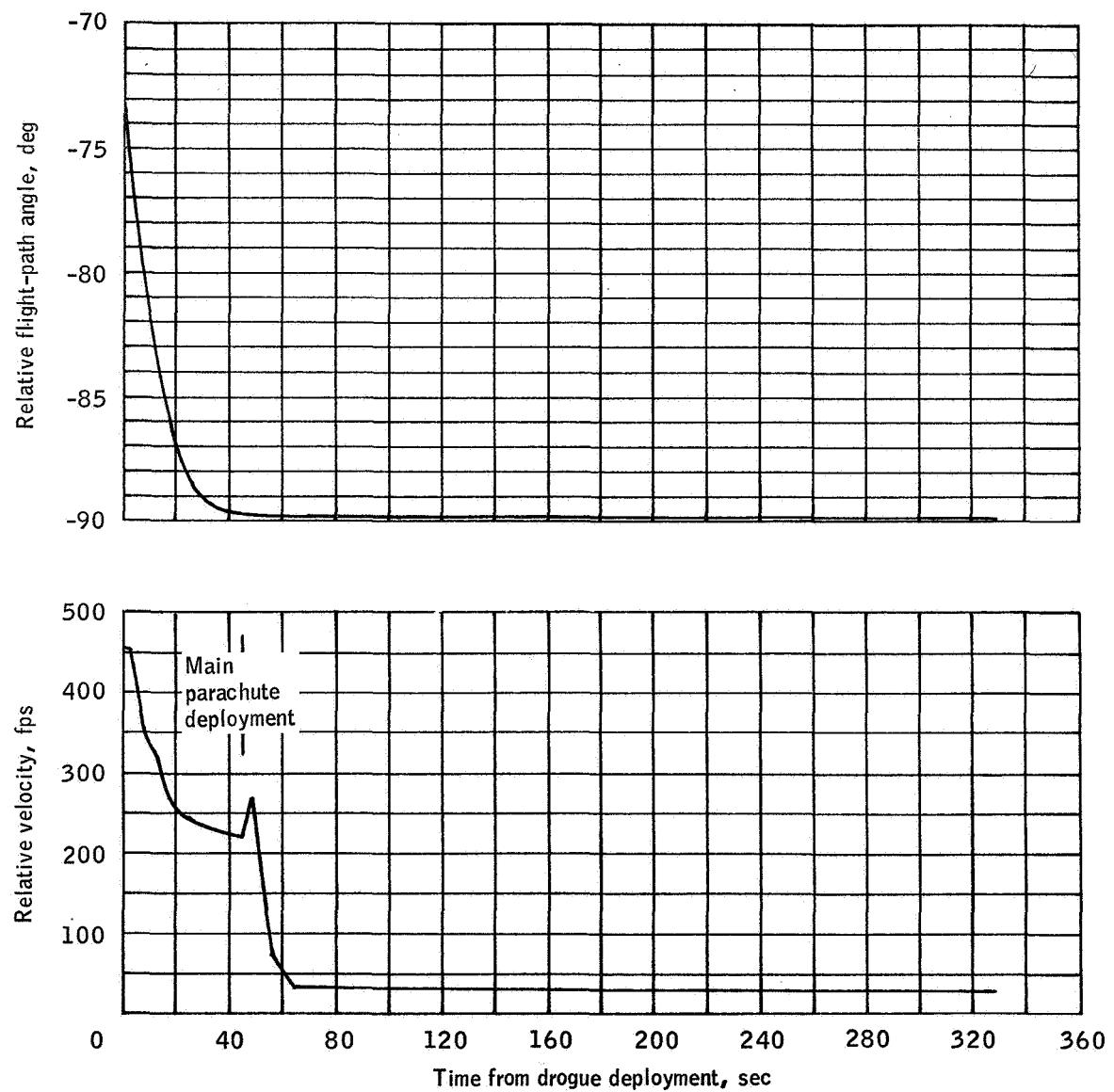


Figure 15. - Relative velocity and relative flight-path angle time histories from drogue parachute deployment.

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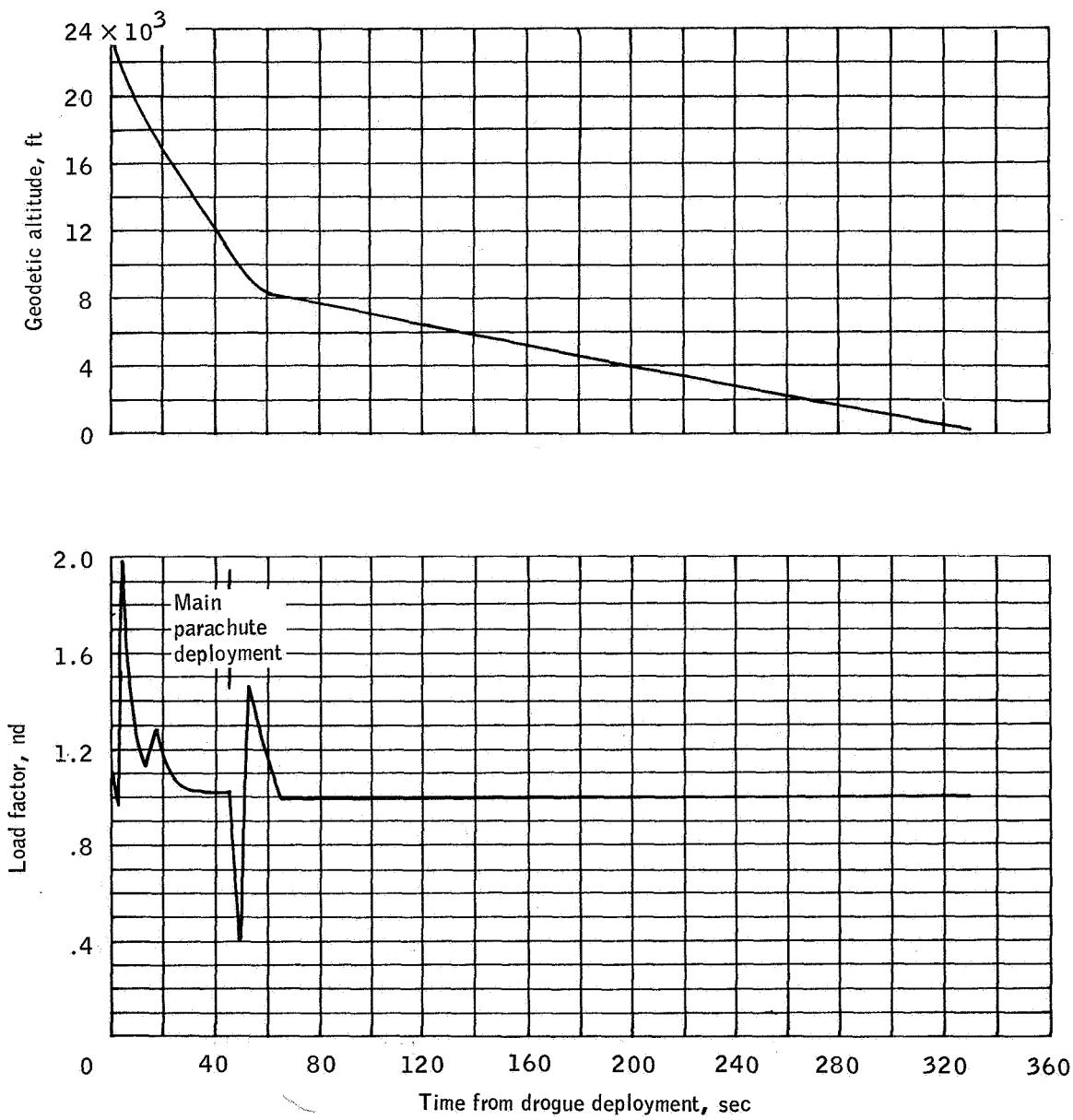
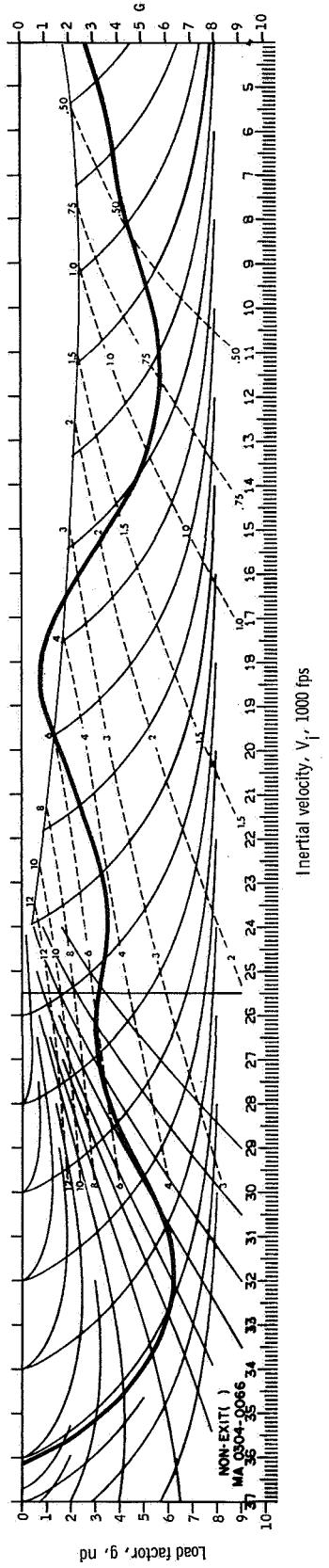
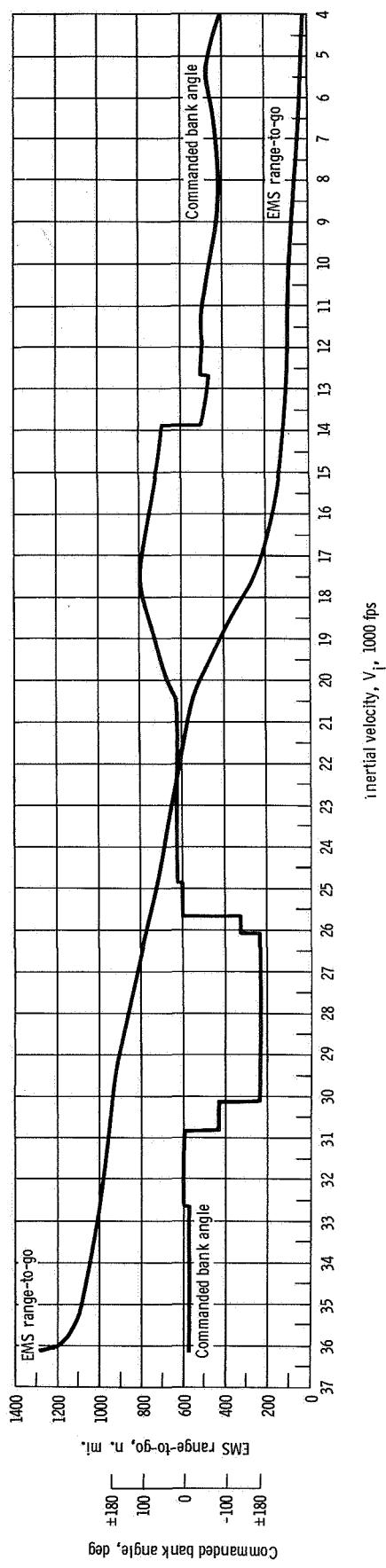


Figure 16.- Geodetic altitude and load factor time histories from drogue parachute deployment.



(a) Load factor versus inertial velocity.



(b) CMC commanded bank angle and EMS range-to-go versus inertial velocity.

Figure 17. - EMS parameters.



APPENDIX

RENDEZVOUS PROFILE REFLECTING TCR G-7



## RENDEZVOUS PROFILE REFLECTING TCR G-7

## SUMMARY

Presented is information concerning the revised rendezvous (starting at LM insertion) for Apollo 11 (Mission G). This appendix updates MSC memorandum 68-FM64-325 dated October 28, 1968, and titled "Currently proposed rendezvous profile for Mission G (LLM)".

## PROFILE CHANGES

The three significant changes that have been made since the last publication of the rendezvous profile are:

1. The insertion orbit apocynthion has been increased from 30 to approximately 45 n. mi. altitude (15 n. mi. below the CSM orbit).
2. A radial velocity component of about 32 fps upward has been added to the LM insertion velocity vector causing a positive flight-path angle at insertion.
3. CSI is now scheduled exactly at the nominal apocynthion time after insertion.

The increase in the apocynthion altitude of the insertion orbit results in a decrease in the LM-to-CSM relative ranges after insertion such that the range at the beginning of the VHF tracking period is approximately 200 n. mi. and, therefore, does not exceed the VHF maximum range specification limit. The radial component at insertion decreases the  $\Delta t$  between insertion and apocynthion--where CSI is performed--by about 4 minutes. Since CDH is essentially fixed at 180° after CSI, this 4-minute decrease between insertion and CSI results in approximately a 4-minute increase in the CDH-to-TPI  $\Delta t$ , as TPI remains fixed at the midpoint of darkness. The decrease in range after insertion and the increase in the CDH-to-TPI  $\Delta t$  were both specifically requested by the crew. The increase in the apocynthion of the nominal insertion orbit is the only acceptable method for decreasing the range at insertion. The range would be decreased if TPI could be scheduled earlier, but this method is obviously not acceptable because the CDH-to-TPI timeline is already rushed. The other method would be to lower the CSM orbit, but this method is undesirable due to descent abort and various dispersion

considerations. Likewise, the radial component at insertion is the only acceptable method for increasing the CDH-to-TPI  $\Delta t$ . TPI cannot be delayed nominally because of lighting constraints; and if CSI should be nominally scheduled prior to apocynthion, a sizeable radial component would result at CDH (an RCS burn).

Since CSI now occurs at apocynthion and at the nominal coelliptic  $\Delta h$  (15 n. mi.), for the perfectly nominal case (i.e., a perfectly circular CSM orbit and no dispersions otherwise), CDH is a zero maneuver. However, if either the CSM orbit is not perfectly circular (as in the data presented in this appendix) or other dispersions exist, a maneuver at CDH will be involved.

#### DISCUSSION OF THE PROFILE

The profile presented here covers the nominal rendezvous sequence starting at LM insertion. At insertion into a  $45.7/9.0$  n. mi. orbit the CSM lead angle is about  $15.5^\circ$ . Due to a 32 fps radial component upward, insertion burnout occurs at a true anomaly of about  $18^\circ$ , and the flight time to CSI (which is performed at apocynthion) is about 51 minutes. For the perfectly nominal case, the CSI maneuver would actually place the LM on a concentric orbit with the CSM at the desired  $\Delta h$ , thereby making CDH a zero maneuver; however, since the CSM orbit is not perfectly circular for the simulated trajectory utilized, a small radial CDH maneuver is necessary to achieve precise coellipticity. The plane change will normally be initiated in conjunction with CSI and completed at PC  $90^\circ$  after CSI (29 minutes prior to CDH) as in the previous profiles. The CDH-to-TPI  $\Delta t$  is now about 37 minutes. Terminal phase remains the same with TPI occurring on a LM-to-CSM elevation angle of  $26.6^\circ$  at the midpoint of darkness. CSM travel angle during terminal phase is  $130^\circ$ . All of the nominal rendezvous maneuvers, except possibly CDH, are performed with RCS Z-axis thrusting to avoid breaking rendezvous radar lock. For this same reason, if CDH is mainly a radial burn, it will probably be applied with X-axis thrusting. PC, which is nominally zero, would be applied with Y-axis thrusting.

#### DISCUSSION OF DATA

Pertinent data for each maneuver are presented in Table I. Column 2 presents the  $\Delta t$  of each maneuver from insertion and column 3 presents the  $\Delta t$  of each maneuver from the previous maneuver. The  $\Delta V$  of each maneuver is presented in column 4. The 2.2 fps  $\Delta V$  for CDH is a radial up component due to the CSM orbit not being perfectly circular. Burn durations are presented in column 5 and are based on 2-jet RCS usage. The burn attitude in column 6 represents the thrust direction measured (starting upward) from the direction of motion. The  $90^\circ$  attitude for CDH indicates a purely

radial-up burn. As indicated in column 7 all maneuvers except PC use Z thrusters. As previously stated, however, if CDH is mainly a radial burn, it will probably be executed with X-axis thrusting. The resultant orbit in column 8 shows that CSI essentially circularizes the LM orbit at 15 n. mi. below the CSM orbit. These altitudes are referenced to the radius of the landing site ( $34^{\circ}$  E,  $2.75^{\circ}$  N).

Figure 1 shows the curvilinear relative motion of the LM in the CSM-centered coordinate system. Figures 2-6 are time histories (with zero time at insertion) of the LM-to-CSM and LM-to-sun elevation angles (figure 2), CSM-to-LM and CSM-to-sun elevation angles (figure 3), relative range (figure 4), relative range rate (figure 5), and CSM lead angle (figure 6).

#### CONCLUSION

The information presented here should adequately define the current LM-in-orbit rendezvous profile for Apollo 11 (Mission G). It is presently planned to incorporate this profile into the Operational Trajectory.

TABLE I.- MISSION G SEQUENCE OF MANEUVERS

| Maneuver | $\Delta t$ from insertion to burn init., min. | $\Delta t$ from previous maneuver, min. | $\Delta V$ , fps | Burn duration, sec. | Burn attitude at burn init., deg. | RCS thruster, usage | Resultant orbit, apo/per, n. mi. |
|----------|---|---|------------------|---------------------|-----------------------------------|---------------------|----------------------------------|
| CSI      | 51.0  | 51.0                                    | 50.1             | 45.0                | 0.0                               | +Z, 2 jet           | 45.2/44.4                        |
| PC       | 80.0  | 29.0                                    | 0.0              | 0.0                 | 0.0                               | $\pm Y$ , 2 jet     | 45.2/44.4                        |
| CDH      | 109.0   | 29.0                                    | 2.2              | 2.0                 | 90.0                              | +Z, 2 jet           | 45.2/45.0                        |
| TPI      | 146.0   | 37.0                                    | 24.7             | 22.1                | 26.5                              | +Z, 2 jet           | 60.8/45.0                        |
| TPF      | 188.5   | 42.5                                    | 31.5             | 28.0                | 305.5                             | -Z, 2 jet           | 60.2/59.3                        |

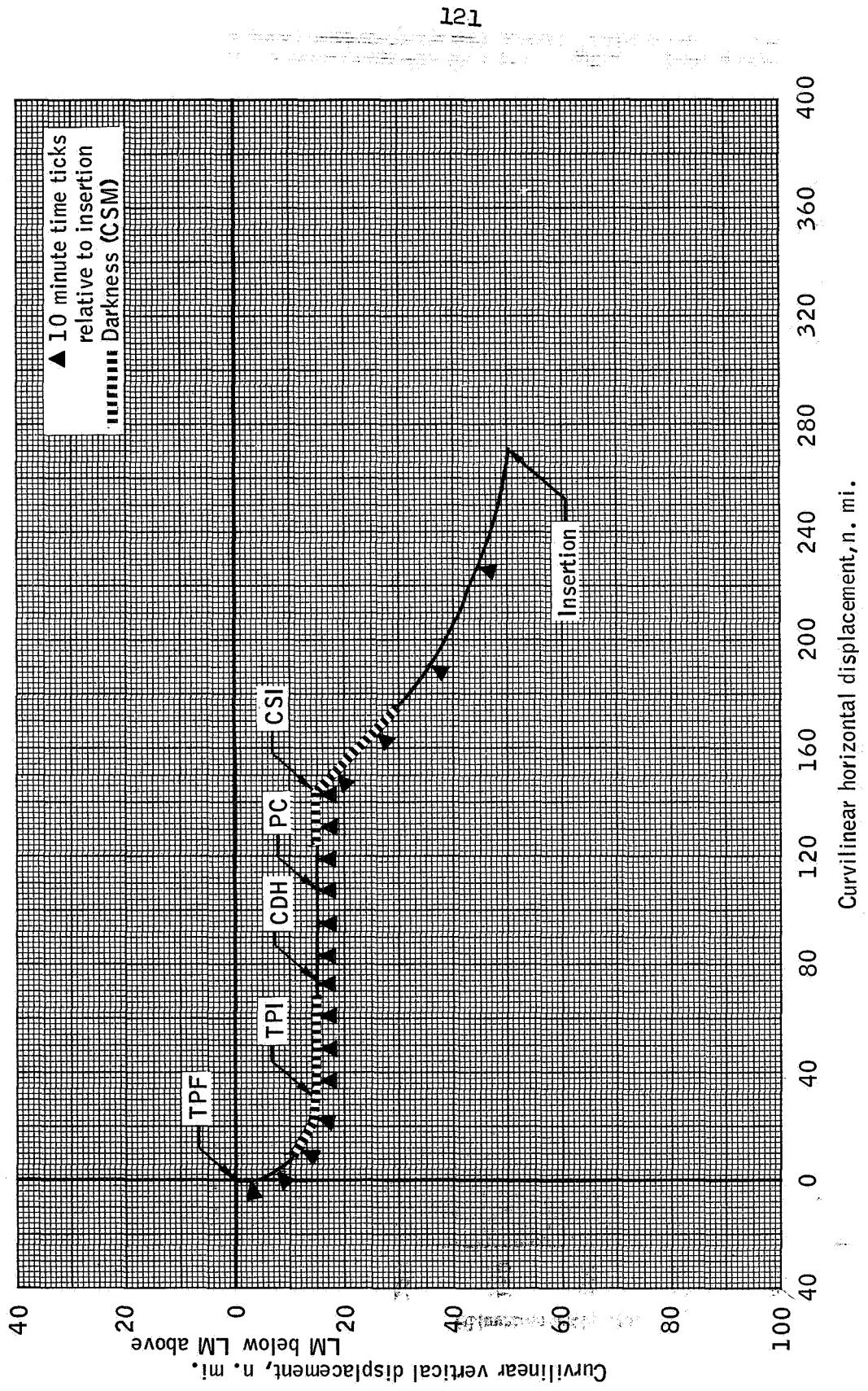


Figure 1.- Relative motion ( curvilinear, CSM-centered ) for nominal LM in-orbit ascent of mission G.

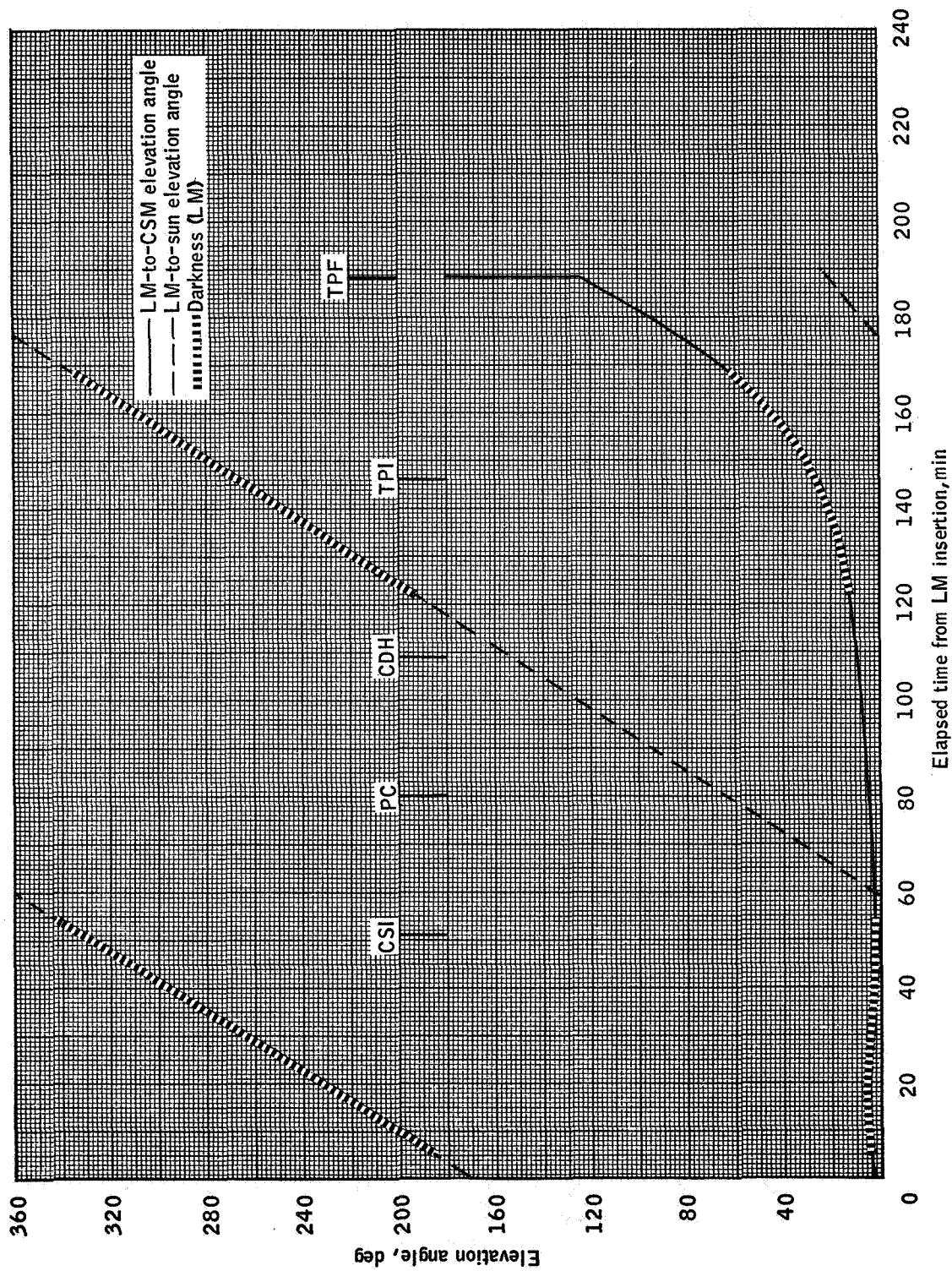


Figure 2.- Time histories of LM-to-CSM and LM-to-sun elevation angles during the nominal LM in-orbit ascent Mission G.

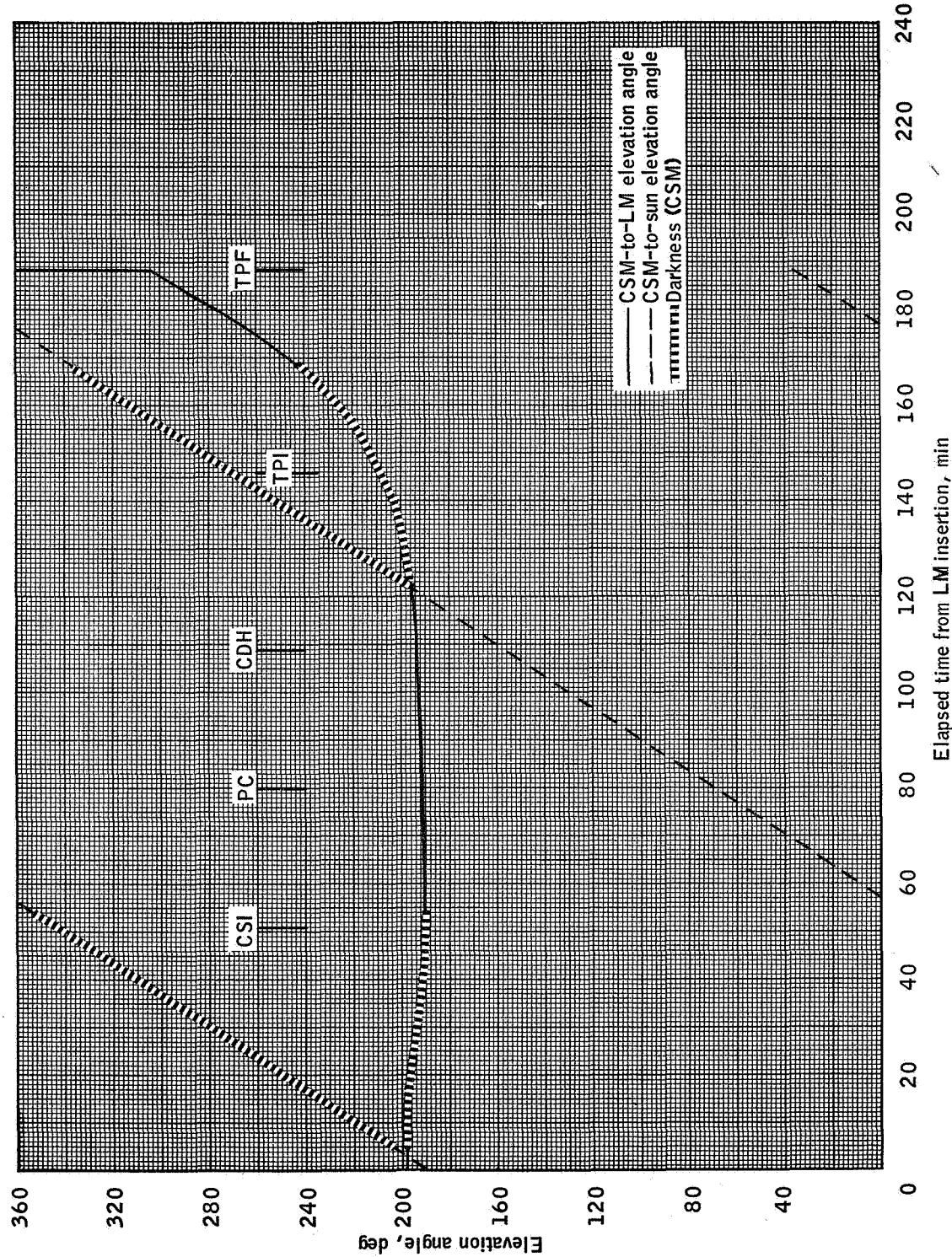


Figure 3.- Time histories of CSM-to-LM and CSM-to-sun elevation angles during the nominal LM in-orbit ascent of Mission G.

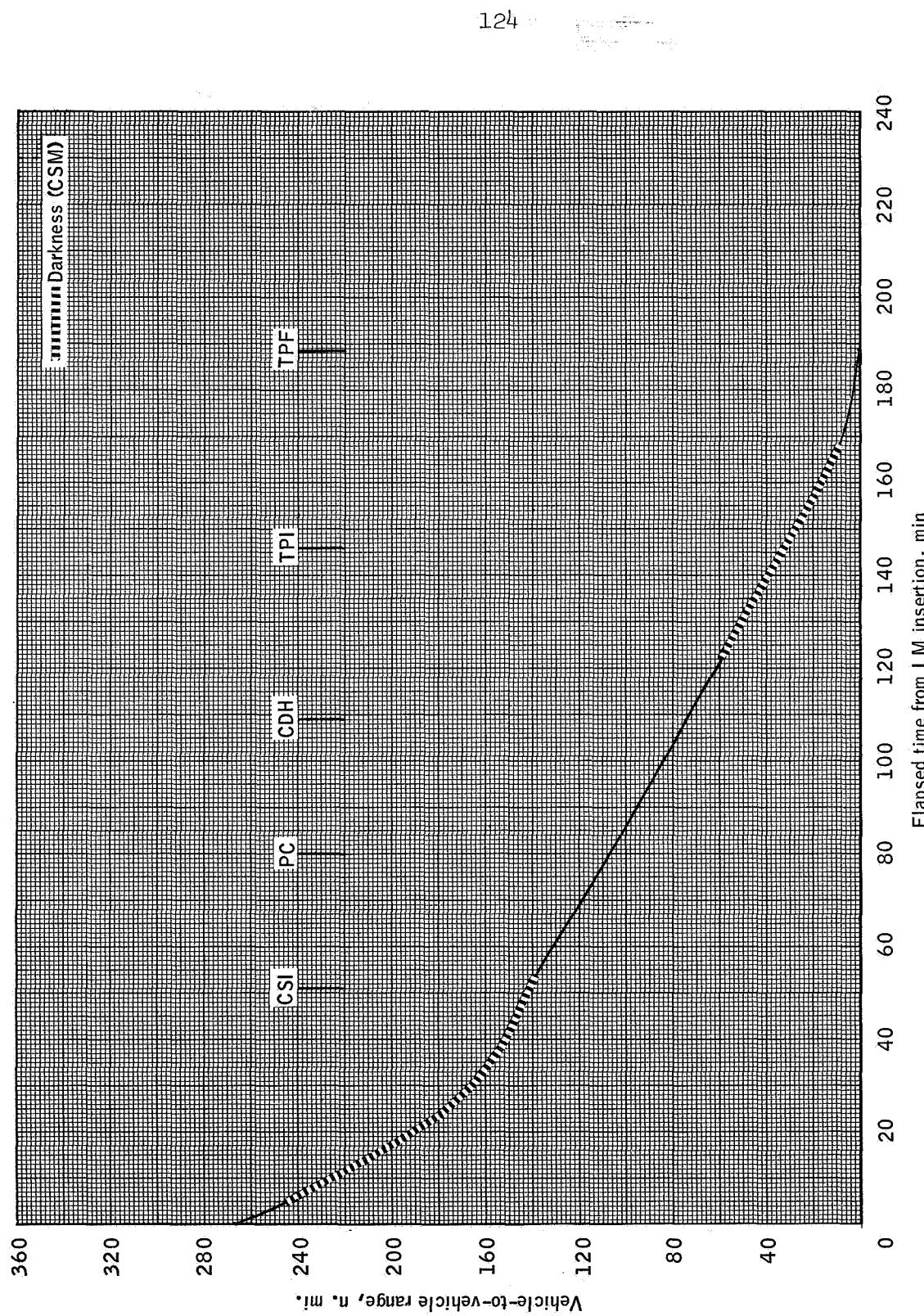


Figure 4. - Time history of vehicle-to-vehicle range during the nominal LM in-orbit ascent of Mission G.

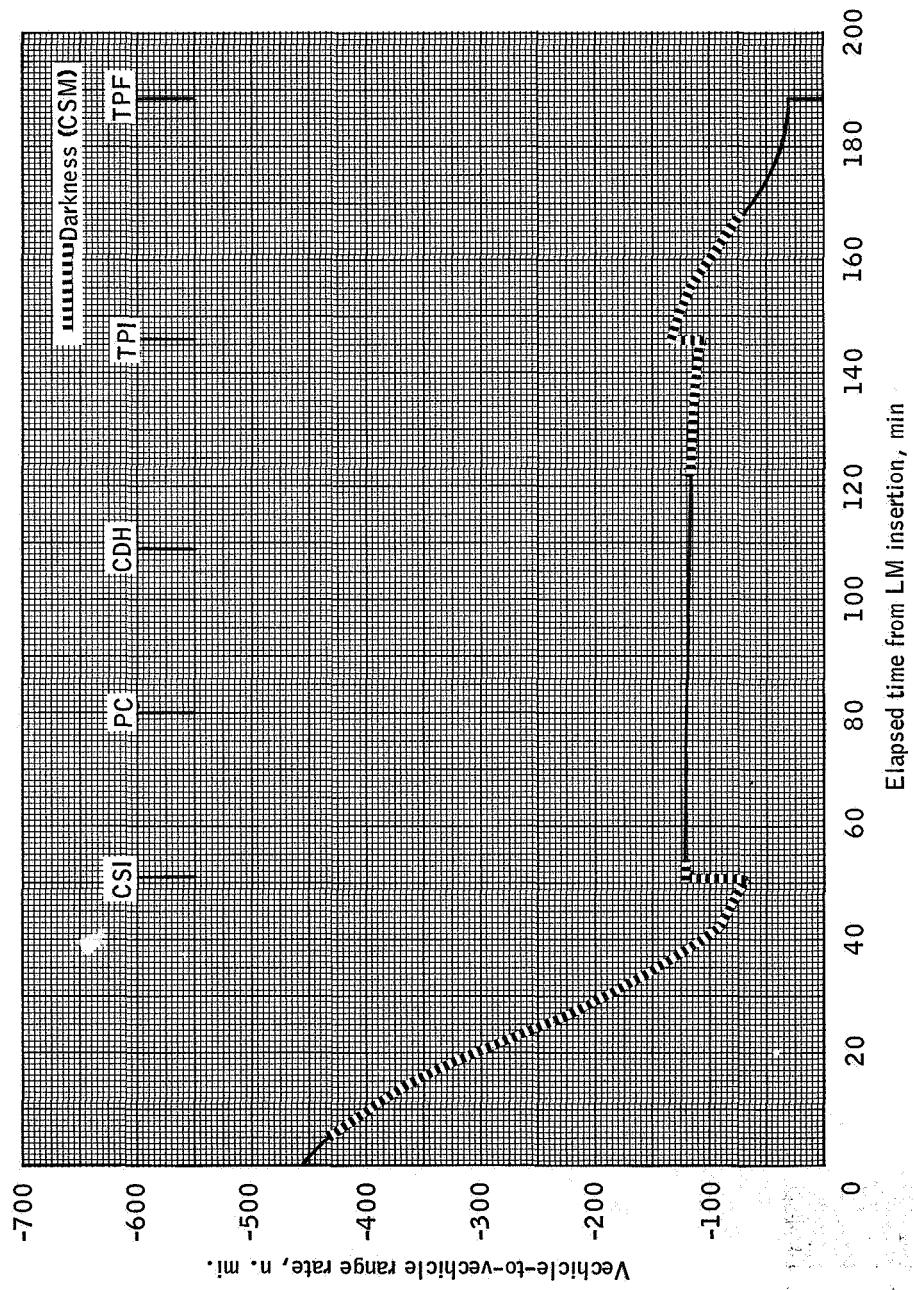


Figure 5.- Time histories of vehicle-to-vehicle range rate during the nominal LM in-orbit ascent of Mission G.

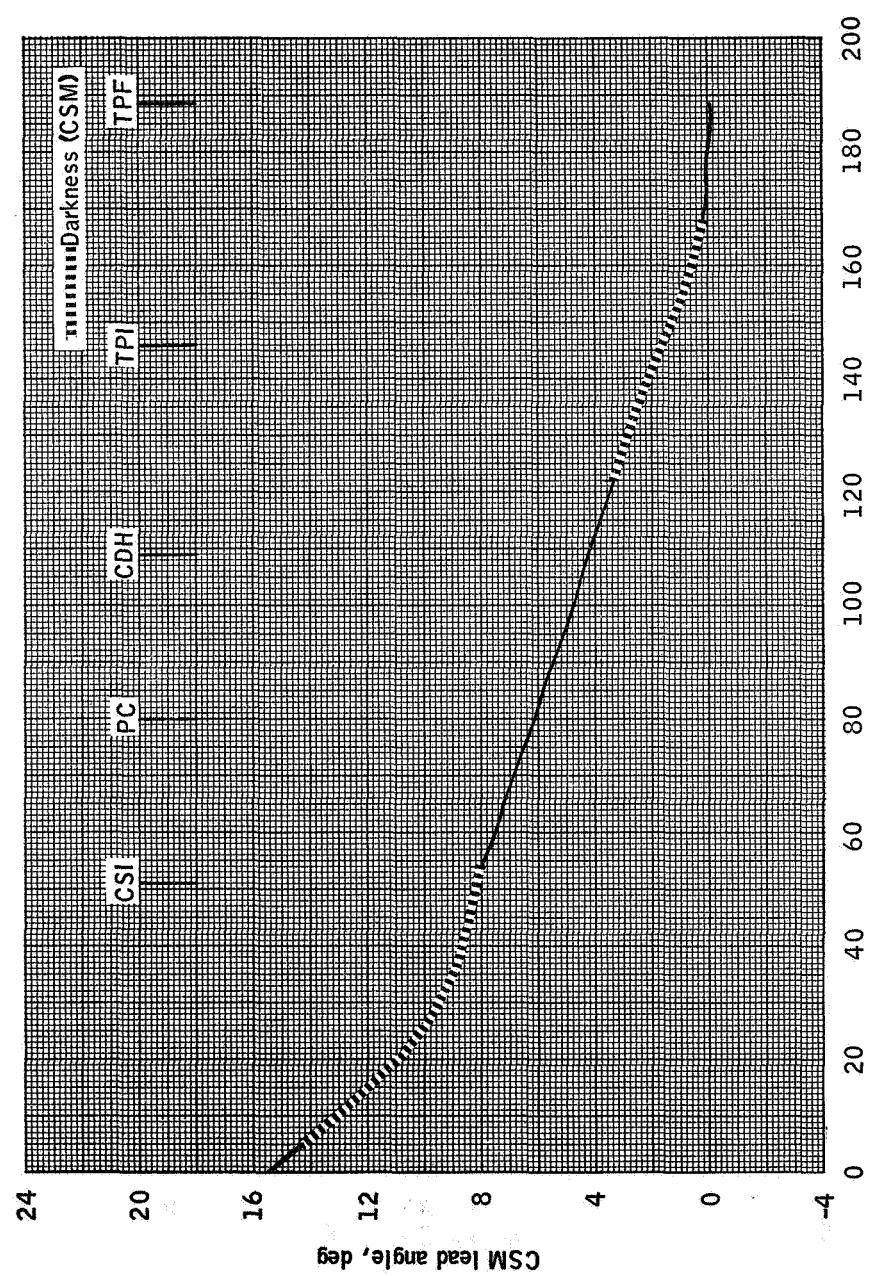


Figure 6.- Time history of CSM lead central angle during the nominal LM in-orbit ascent of Mission G.

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